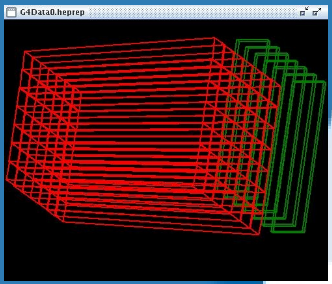


Crystal Calorimetry

Subtitle

A Totally active dual read out calorimeter for the Muon Collider

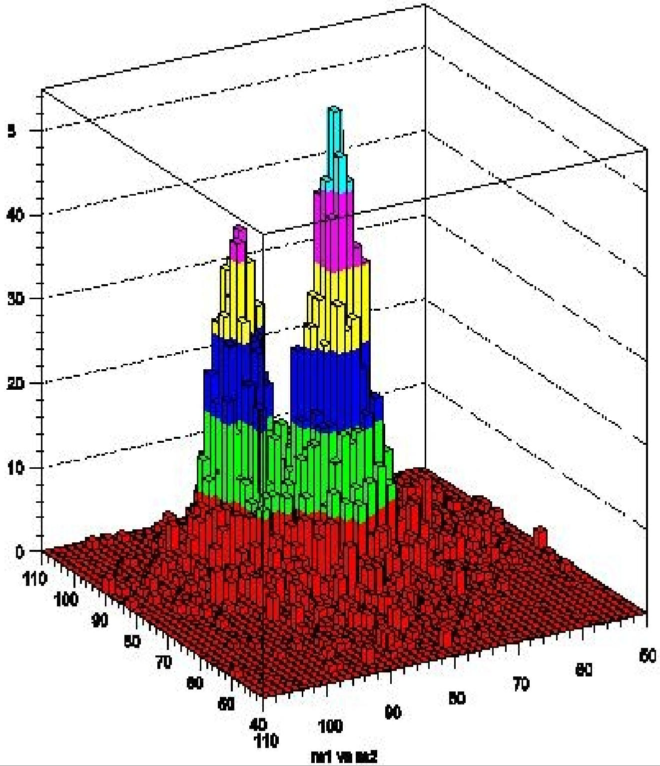
Muon Collider Physics Workshop 10-12 Nov. 2009

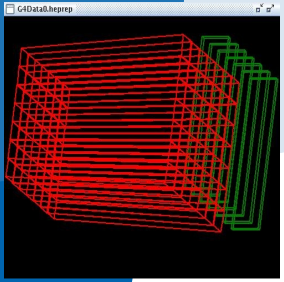
Hans Wenzel

Fermilab

Adam Para, Steve Magill,
GiovanniPauletta, Hans Wenzel
Krzysztof Genser, Anna Driutti,
Nayeli A Rodriguez- Briones,
Jeffrey Hill,Paul Rubinov, Eric Shinn,
Diego Cauz....

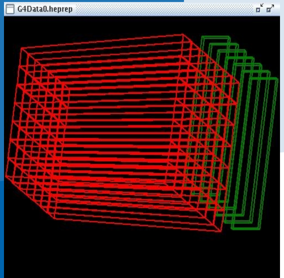
12th November 2009





Outline

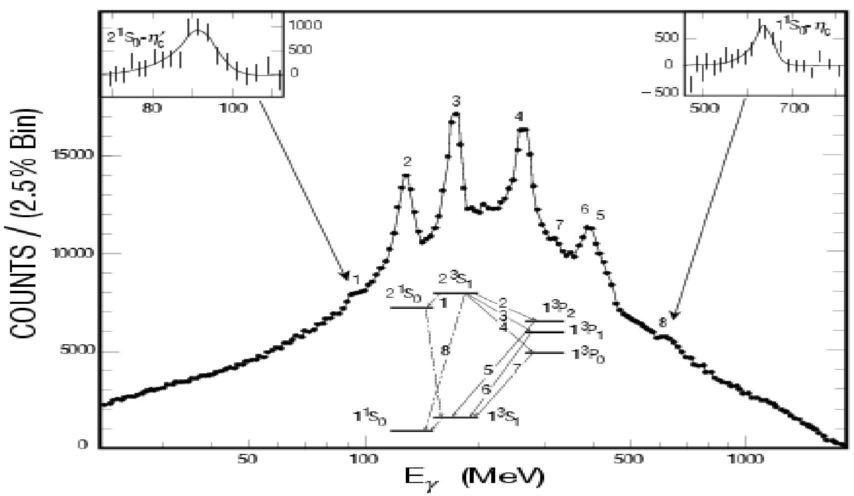
- Motivation
- Principle of a dual read out calorimeter
- The software environment
- The ccal02 detector.
- Analysis:
  - Calibration using electrons.
  - Obtaining the dual read out correction.
  - Resolution for single π^-
  - Effects limiting the resolution: leakage, energy dependence of dual read out correction that's not accounted for.
  - Jet reconstruction performance.
- Can we trust the MC (Geant 4)?
- Effects affecting the calorimeter performance
- Crystals in a test beam
- Conclusions



Motivation

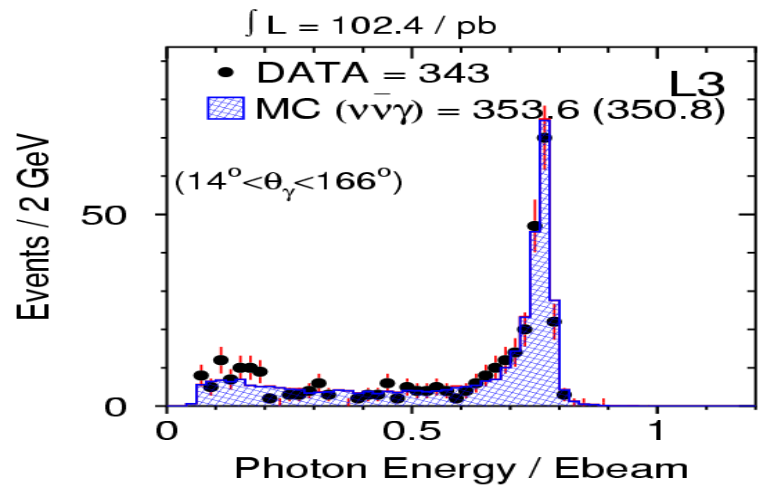
- Lepton Colliders provide a clean environment and aim for high precision measurements complementing discovery machines like the LHC. Don't what physics scenarios we will finally encounter. We should be ready for all scenarios and aim to build the best possible detector/calorimeter.

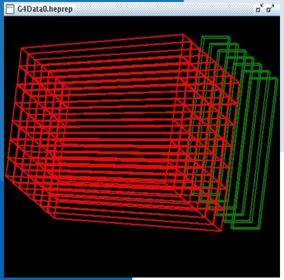
Charmonium System Observed Through Inclusive Photons: CB



SUSY Breaking with Gravitino

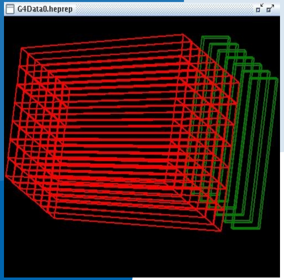
$e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma \{\tilde{G}\tilde{G}$ ¿





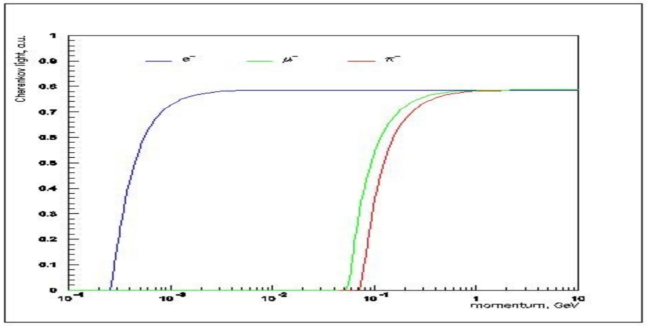
Motivation (cont.)

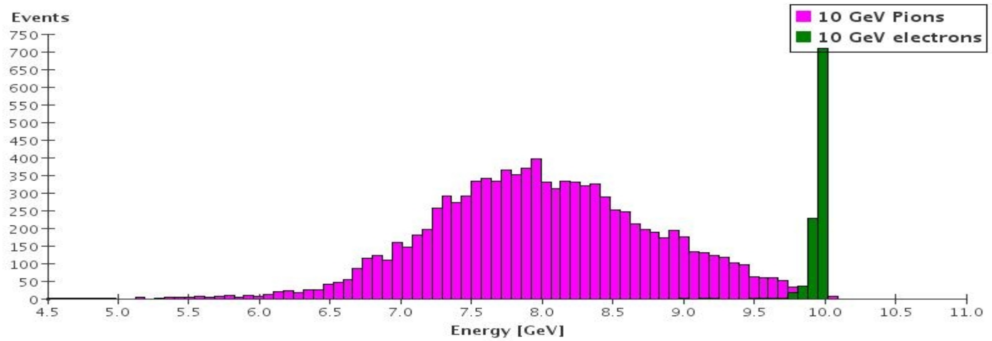
- Totally active dual read out crystal calorimeter:
  - Excellent EM calorimeter.
  - Excellent hadron calorimeter:
    - Totally active, not a sampling calorimeter, even large sampling fraction induces significant stochastic term (dependent on particle type).
    - Dual read out (see later).
  - Longitudinal segmentation helps to detect and correct for leakage.
  - While not a PFA calorimeter, segmentation is fine enough so that particle flow algorithms can be applied (Steve Magill).
  - Dense scintillating crystals and new economical photo detector like SiPMT are what makes this possible.

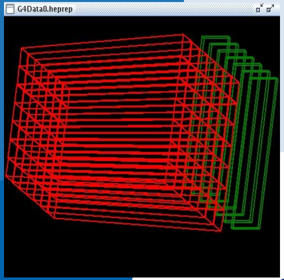


Principle of a dual read out calorimeter

- Detect separately scintillation and Cerenkov light (same Volume)
- Scintillation light is a precise measure of the total energy released in the calorimeter (~total path length of the charged particles in a shower).
- Cerenkov light is a precise measure of the total path length of the relativistic particles (β>1/n) in the shower.
- Calibrate C=S for electron showers (spread of both signals very small)
- Hadron showers with large C/S --> large electromagnetic component, small missing energy.
- Hadron showers with low C/S --> purely charged hadrons, large amount of missing energy.

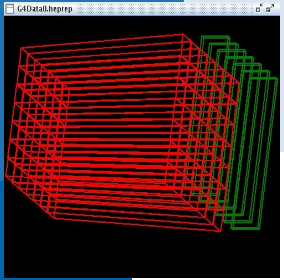






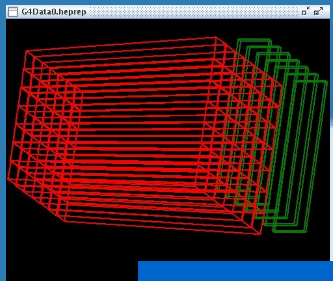
The software environment:

- **SLIC:** Geant 4 based framework for detector simulation.
  - XML based detector description (geometry and sensitive detectors):
    - Easy to implement various detector variations: materials, density, em and had segmentation, optical properties, …
    - Executing a simple script creates all files necessary for simulation and analysis.
  - Variety of physics lists.
  - **LCIO** event output
- Using **SLIC** allows us to make use of the entire SID framework: **SLIC (C++), lcsim.org (netbeans), WIRED, JAS3, LCIO Event Browser (JAVA)** ..... → this allows us to study physics performance as part of a complete detector. Very nice development environment.
- If one prefers **ROOT** we have a **LCIO** to root converter for the relevant lcio classes.
- Easy to run SLIC on the grid → we have Grid scripts: make it easy to generate large data sets, takes care of names, random seeds etc., http://confluence.slac.stanford.edu/display/ilc/How+do+I+use+the+OSG+Grid
- Calibration and analysis is automated using the **lcsim.org**



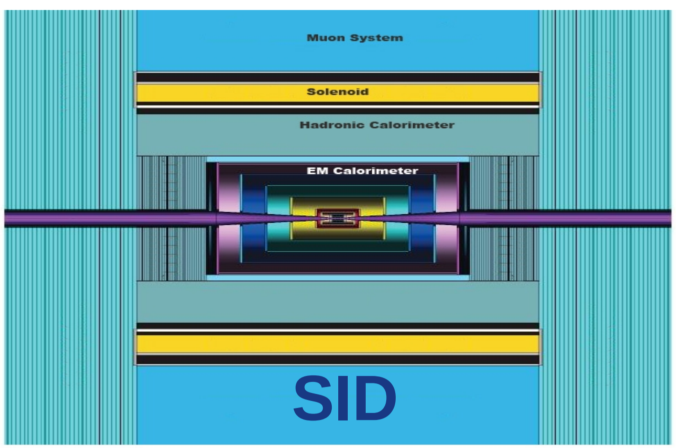
What needed to be done to simulate total absorption dual read out calorimeter in SLIC

- Need to add optical physics (Cerenkov,Scintillation etc.,) → now can be used with any physics list.
- Need to be able to add optical properties to materials in detector description e. g. refraction index/absorption as function of photon energy.
- Sensitive detector needs to be able to produce multiple hit Collection (Energy deposition, Cerenkov) → this is allowed in GEANT 4 but SLIC in its original form only allowed for one Hit collection per sensitive collector.
- Implement special optical calorimeter class:
  - Register energy deposition (Edep hits).
  - deal with optical photons. We don't track optical photons but kill them after the first step and add their energy to the Cerenkov hits.



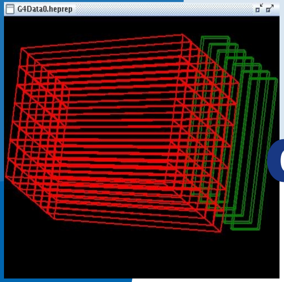
The CCAL02 detector
(Crystal Calorimetry version of SID)

				BGO		$PbWO_4$	
Name	Layers	Thickness/Layer	Segmentation	X_0	λ_I	X0	ll
		[cm]	[cm x cm]				
ECAL Barrel	8	3	3 x 3	21.4	1.1	27	1.3
HCAL Barrel	17	6	5 x 5		4.7		5.7
Total Barrel	25				5.8		7
ECAL Endcap	8	3	3 x 3	21.4	1.1		1.3
HCAL Endcap	17	6	5 x 5		4.7		5.7
Total Endcap	25				5.8		7



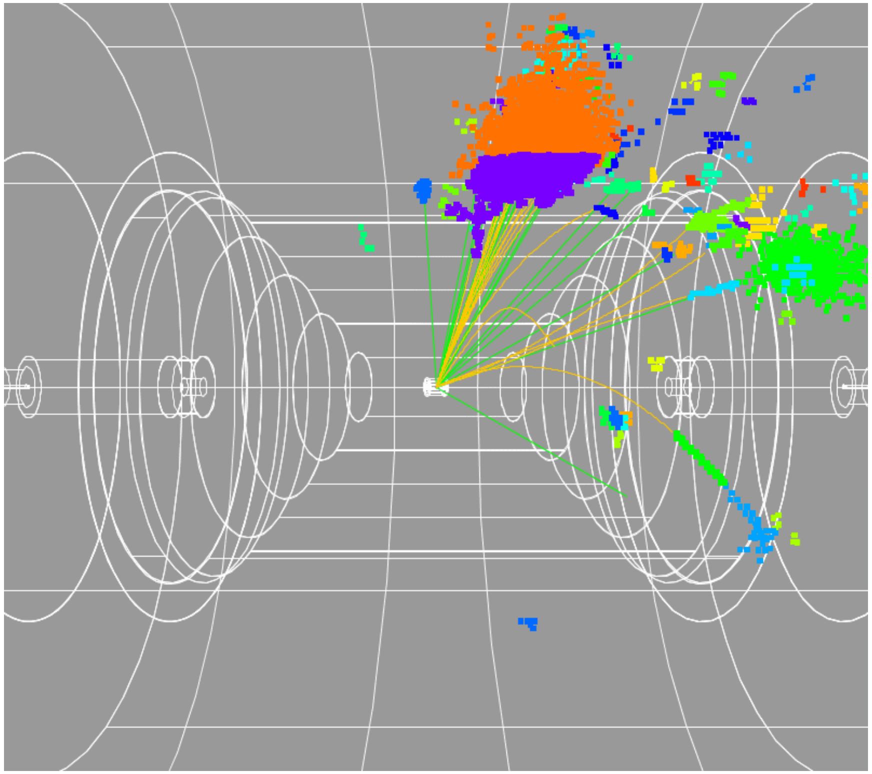
Material	Density	Rad. len. X_0	λ_I len.
	[g/cm3]	[cm]	[cm]
BGO	7.13	1.12	21.88
$PbWO_4$	8.3	0.9	18
SCG1-C	3.36	4.25	45.6

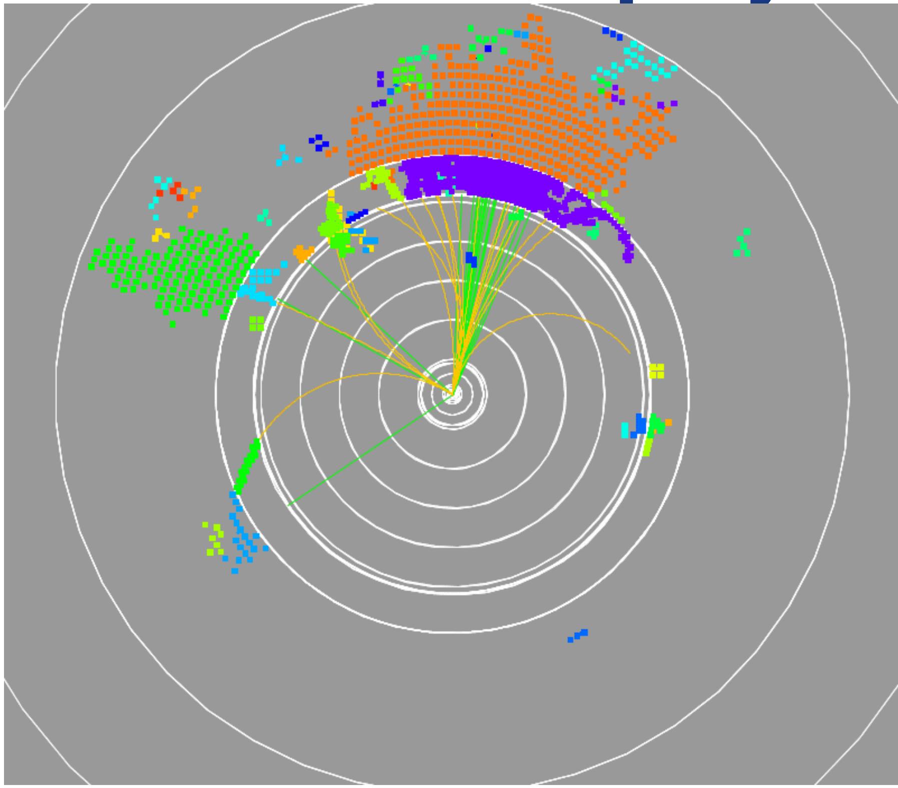
Monte Carlo: BGO with 15.0 g/cm^3



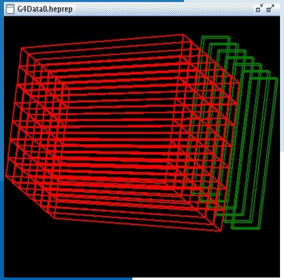
CCAL02 Scintillation response as displayed in the Wired event display

ZZ->qqνν



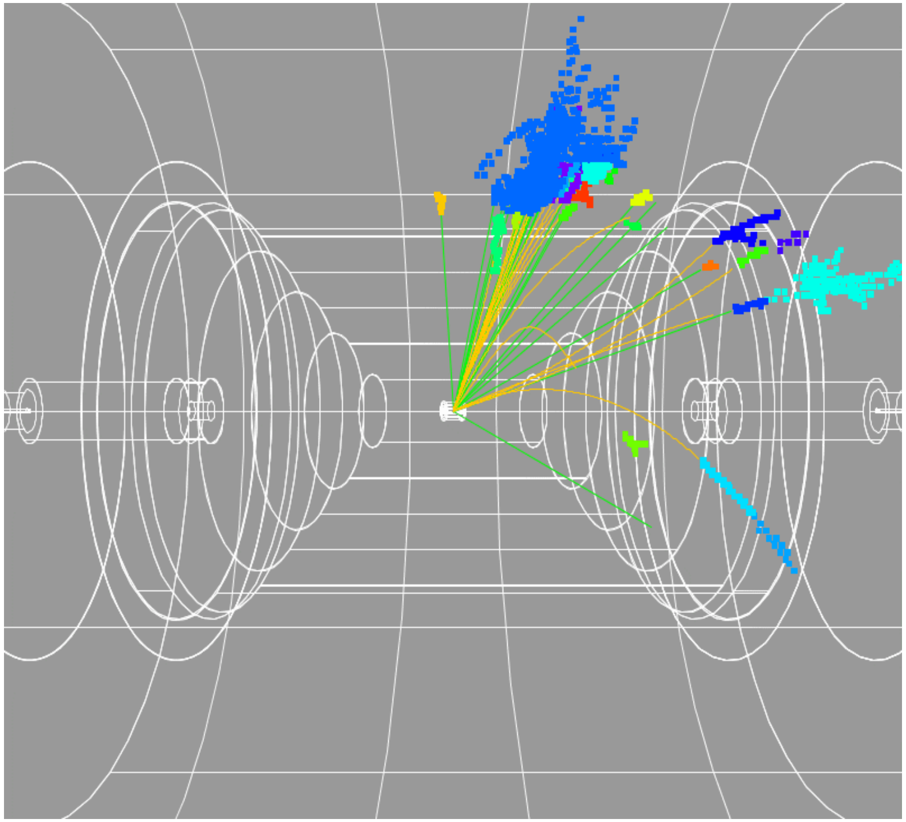


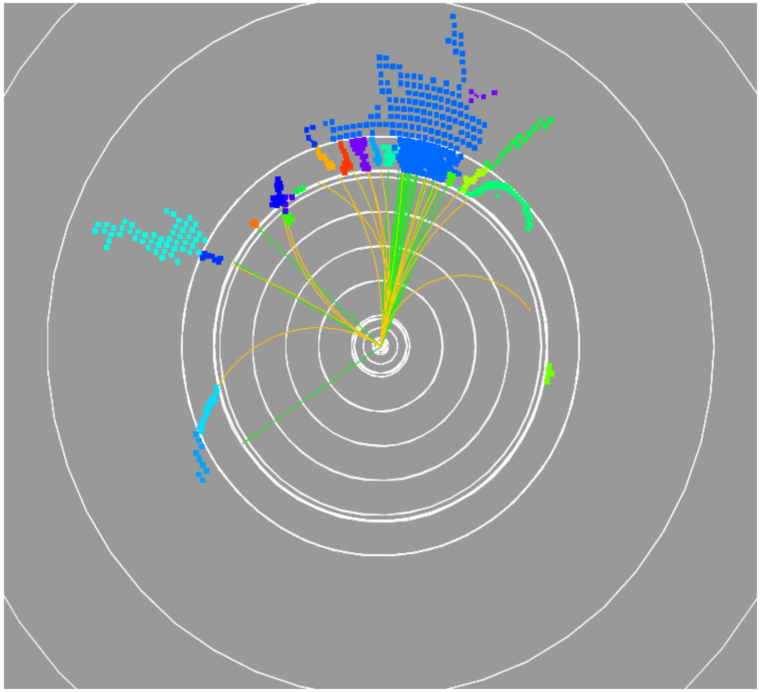
Digisim

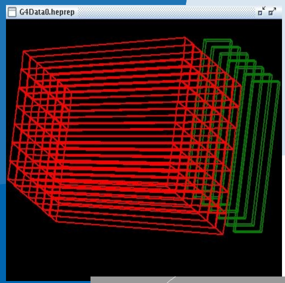


CCAL02 Cerenkov response as displayed in the Wired event display

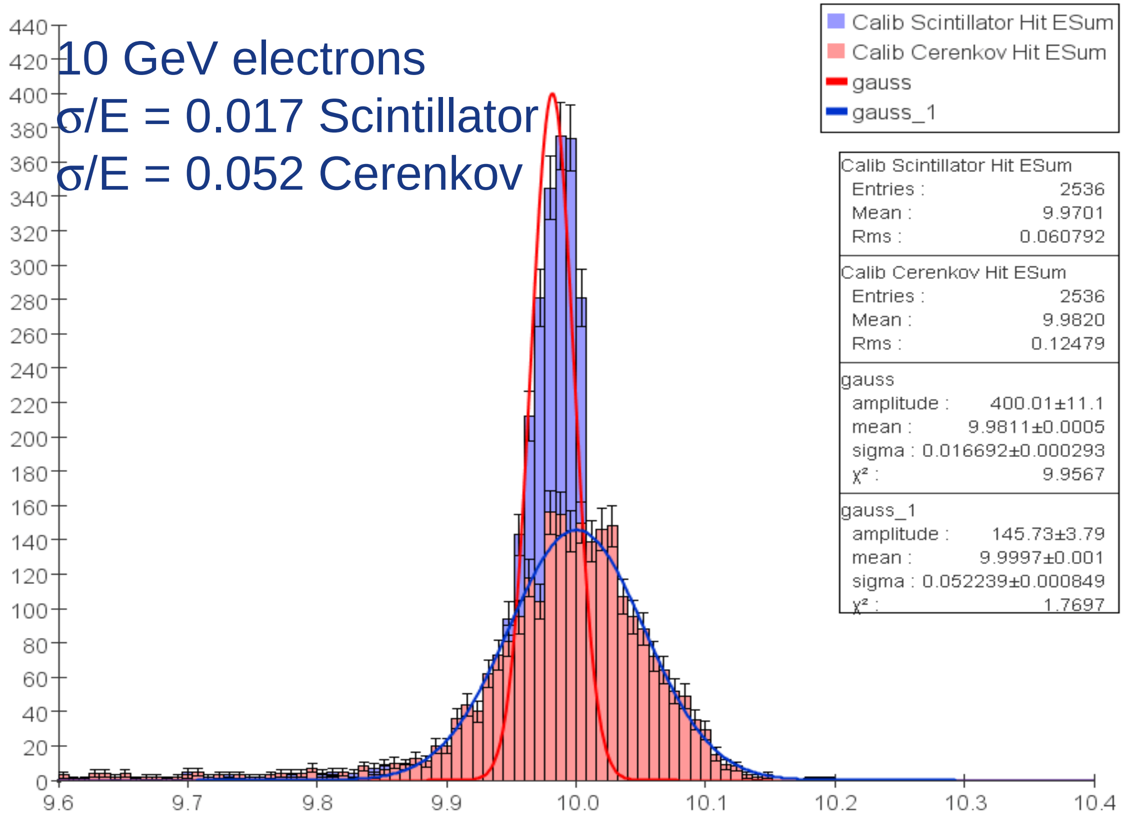
ZZ->qqνν



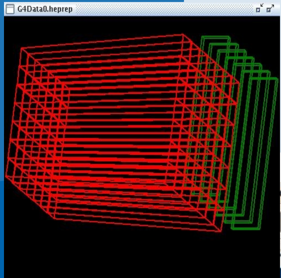




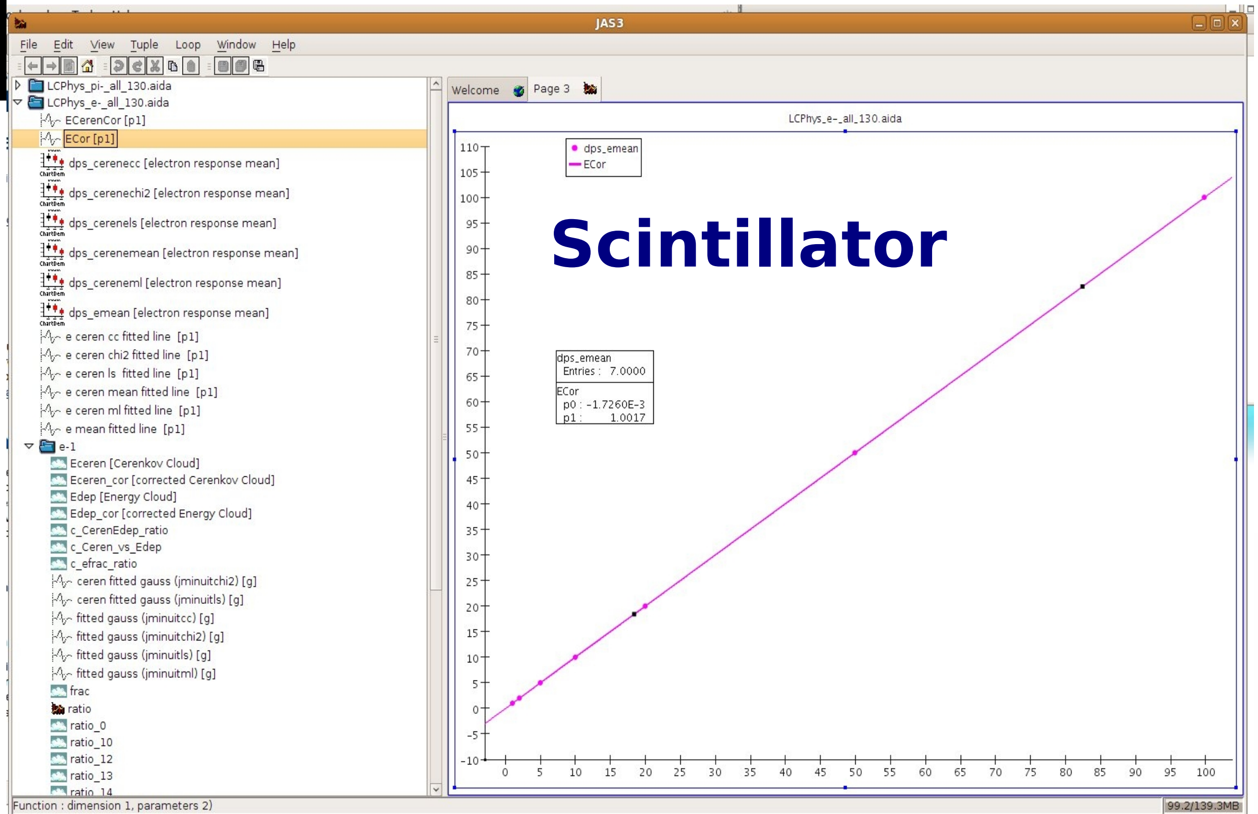
Analysis: Electron Calibration for Scintillator, Cerenkov

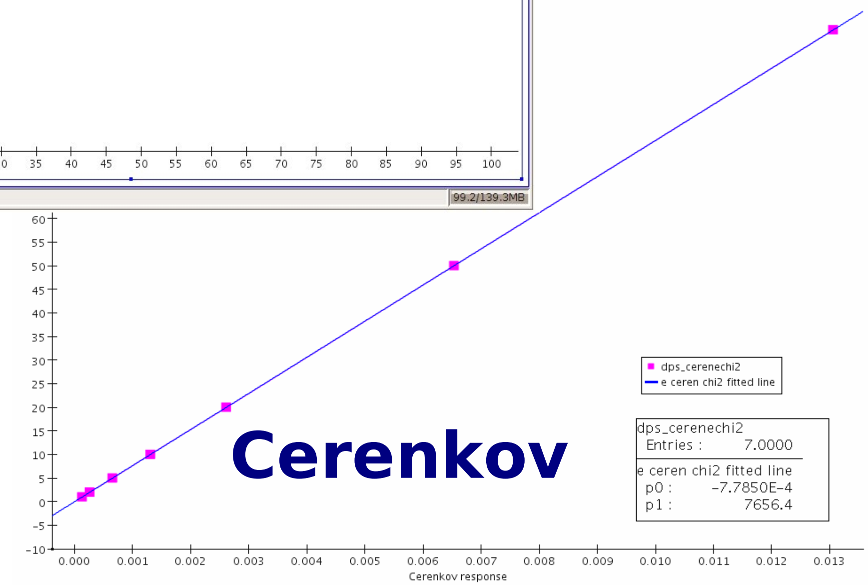


$S = 1.004 \times s_{raw}$ $C = 7692 \times c_{raw}$



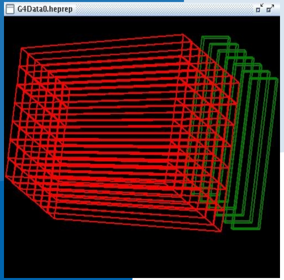
Electron Calibration for Scintillator, Cerenkov

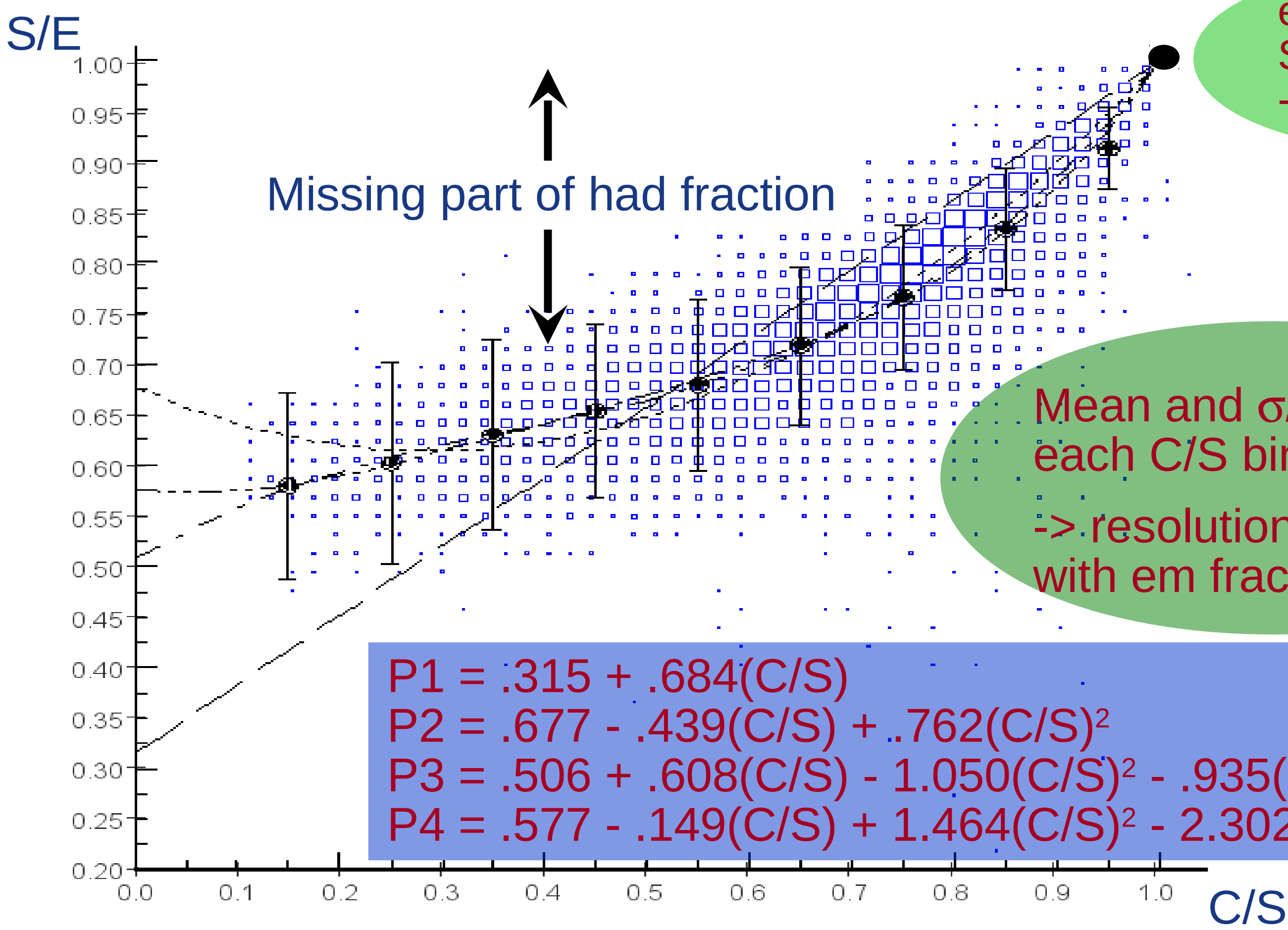




Use single electrons of
1.0, 2.0, 5.0, 10.0, 20.0, 50.0, 100.0 GeV
To estimate energy scale.

Polynomial Correction Functions: E=S/Pn





em fraction = 1
S/E, C/S = 1
-> calibration

Mean and σ/mean of fit in each C/S bin plotted

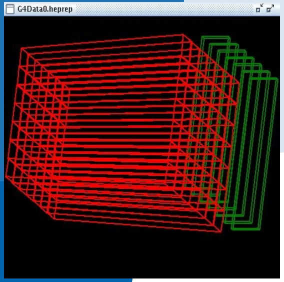
-> resolution improves with em fraction

$P1 = .315 + .684(C/S)$

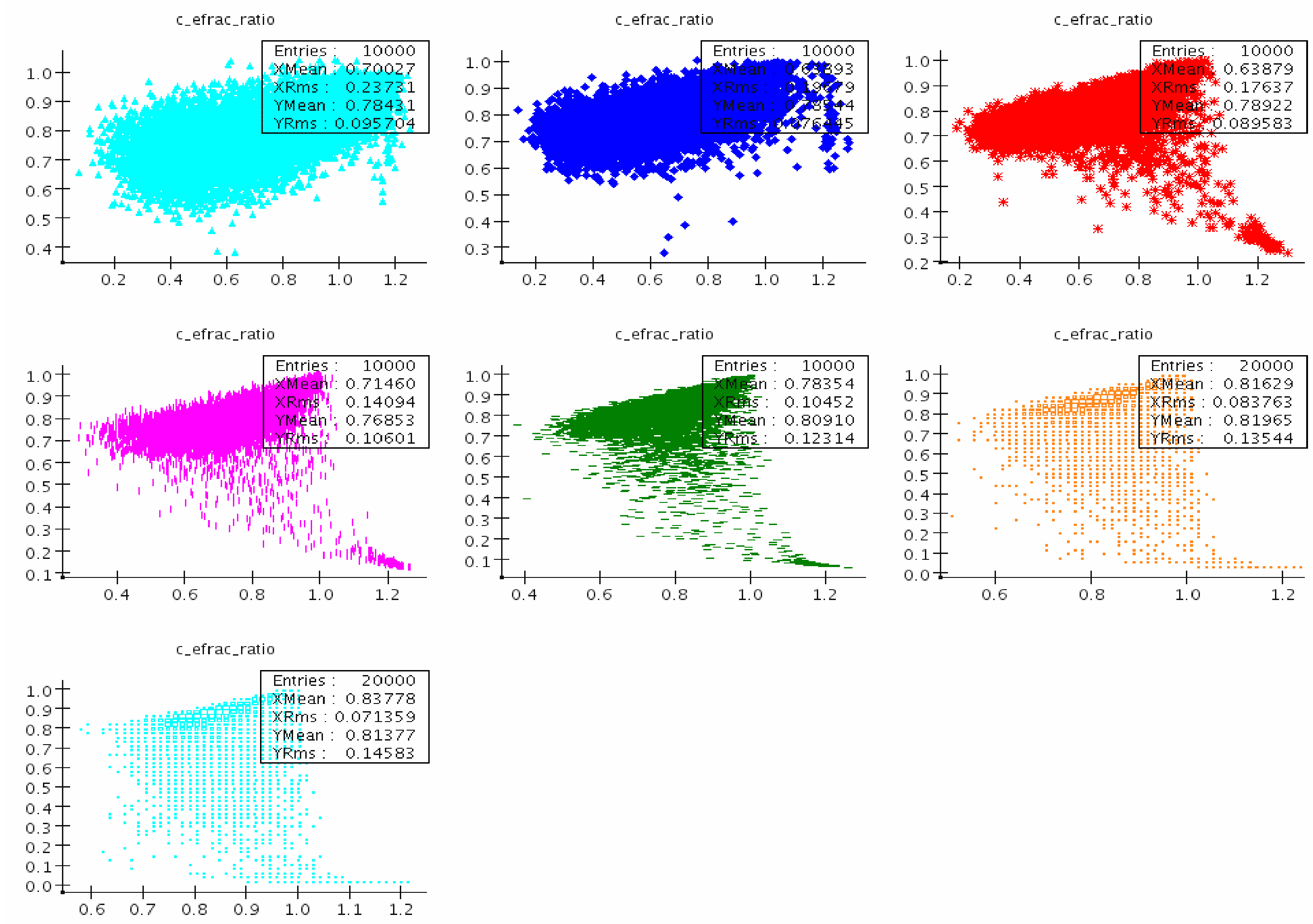
$P2 = .677 - .439(C/S) + .762(C/S)^2$

$P3 = .506 + .608(C/S) - 1.050(C/S)^2 - .935(C/S)^3$

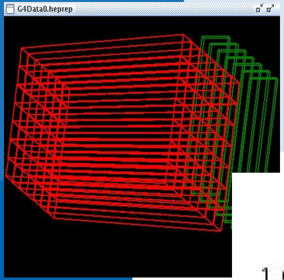
$P4 = .577 - .149(C/S) + 1.464(C/S)^2 - 2.302(C/S)^3 + 1.410(C/S)^4$

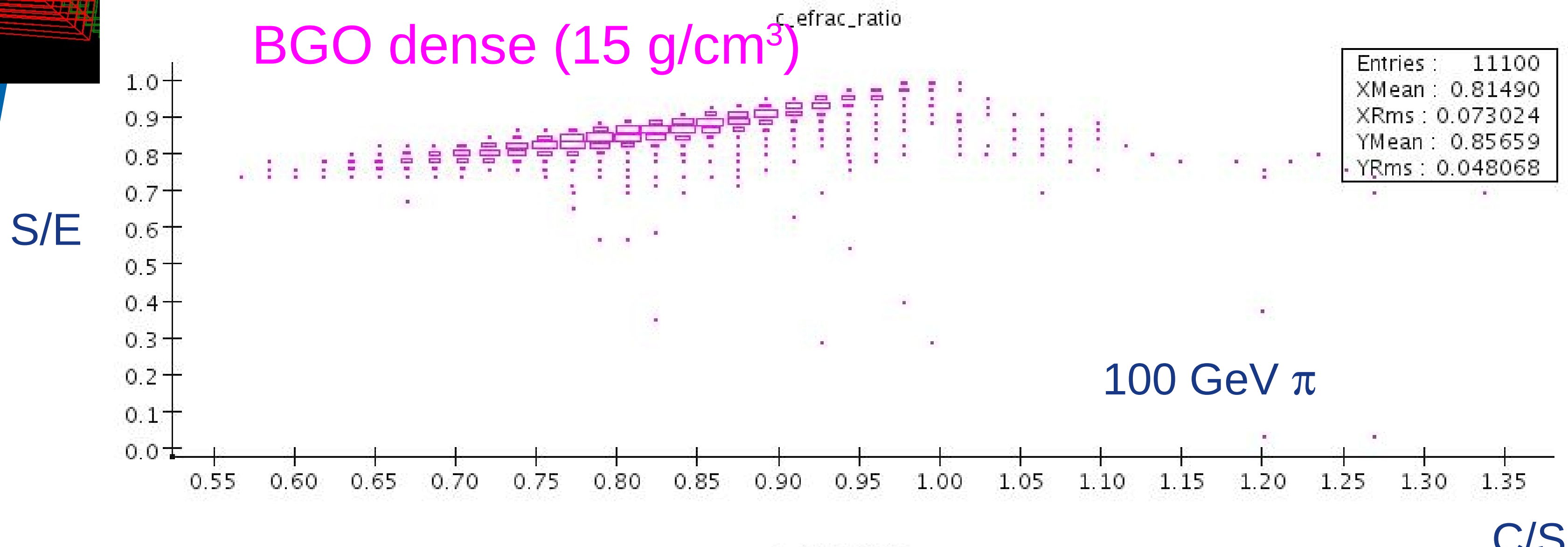


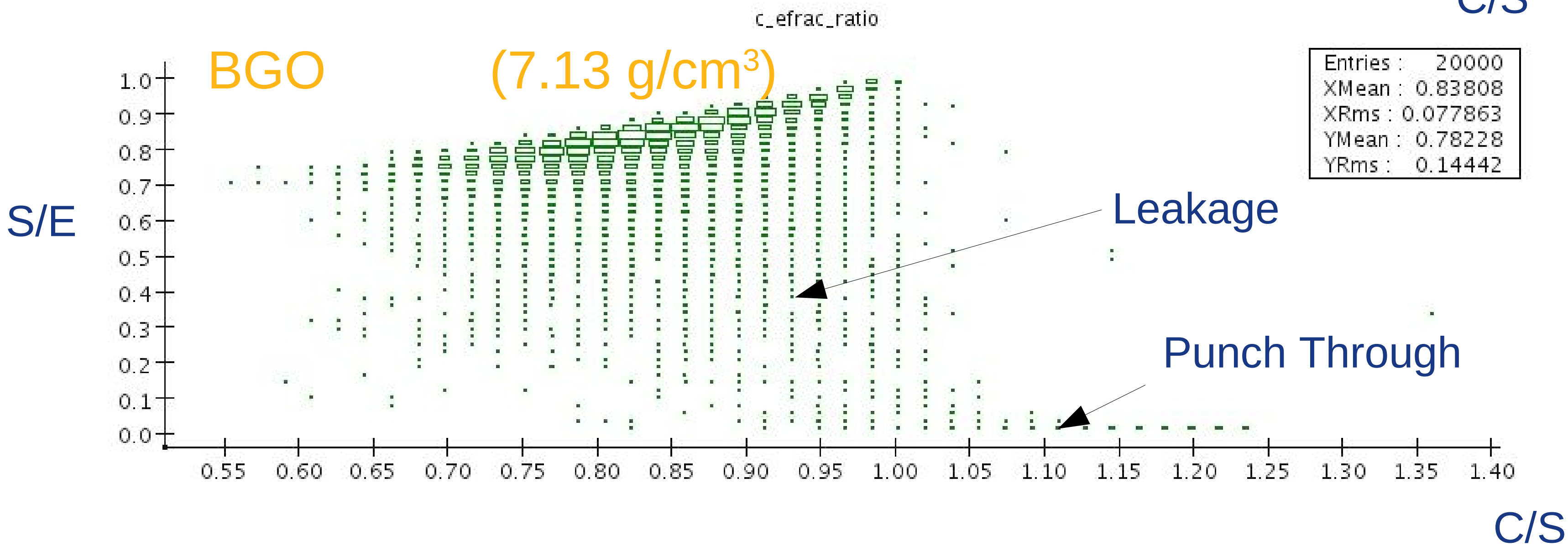
DualCorrection:S/E vs C/S all energies combined

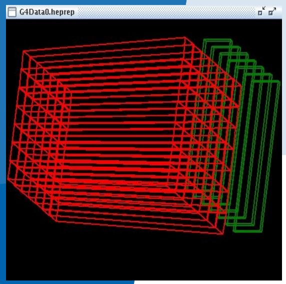


Leakage has to be considered when obtaining dual correction!

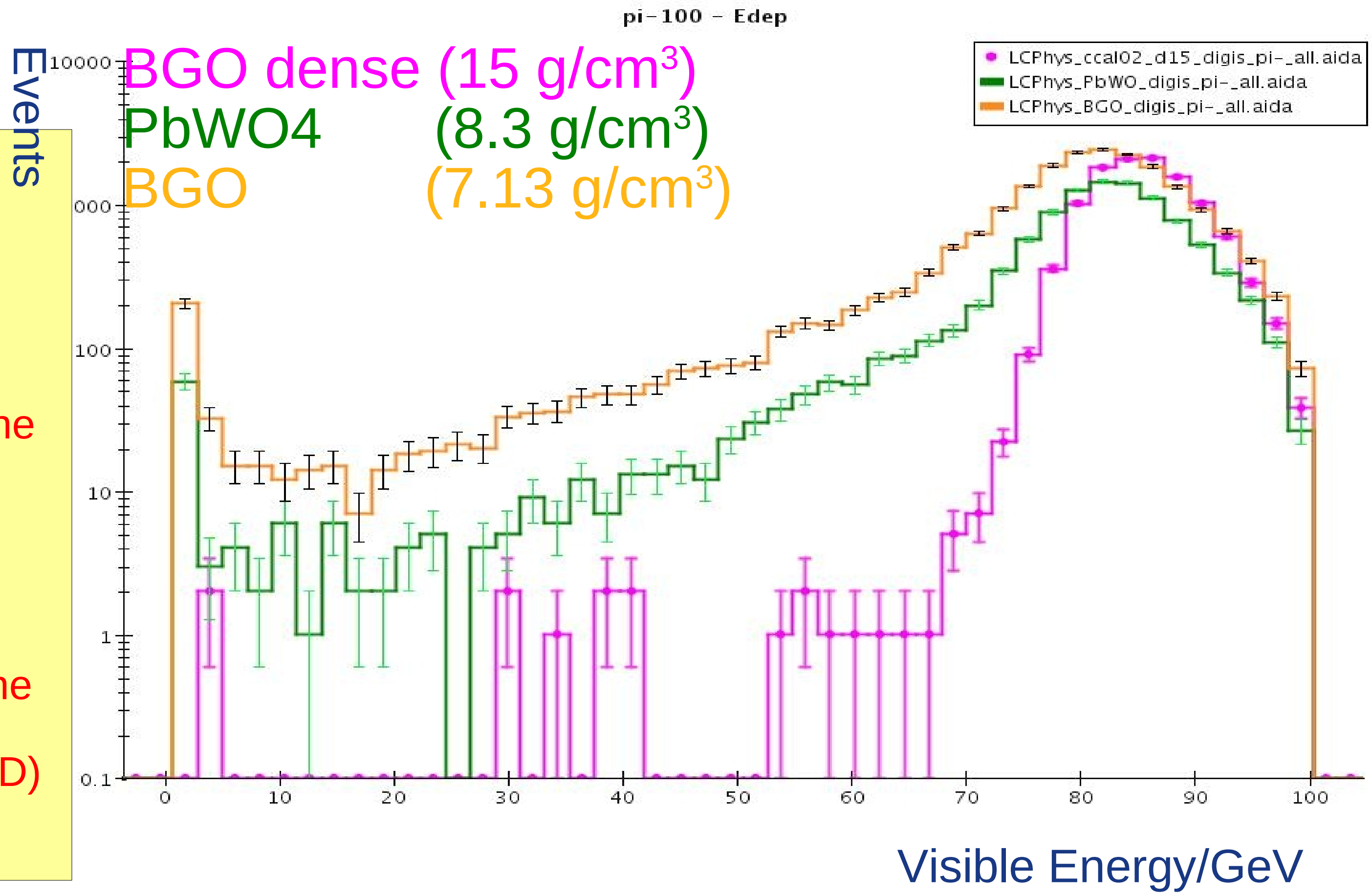








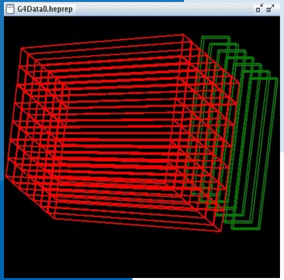
100 GeV π leakage for BGO/PbWO4/ BGO dense



The leakage energy fluctuates and the fractional fluctuation increases with energy until it exceeds the stochastic term and sets the limit on the achievable energy resolution.

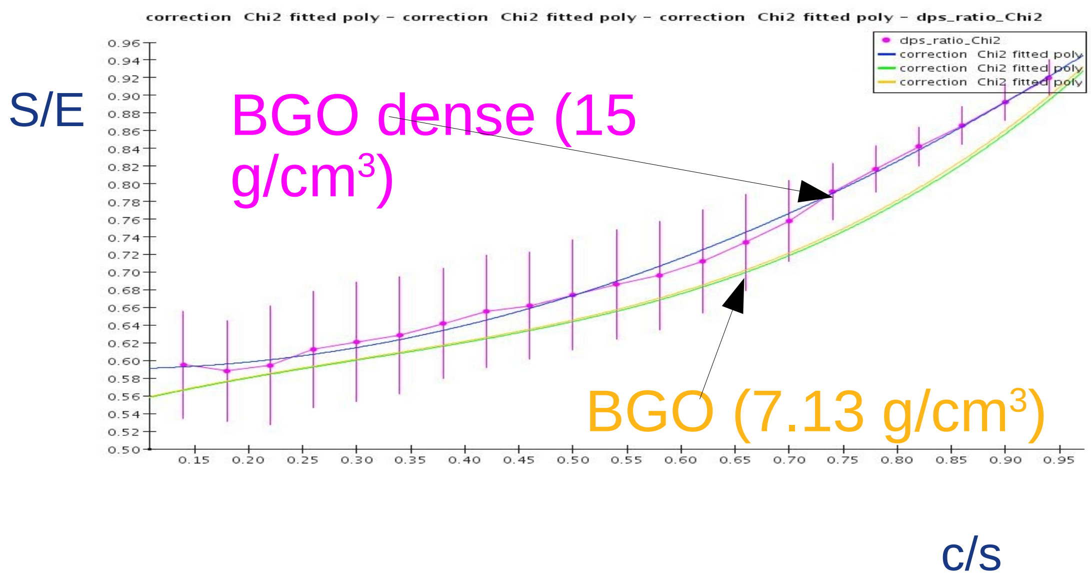
Leakage fluctuations depend on:
-the starting point of the hadron shower (Interaction Depth or ID)
-the extension of the shower

Leakage is of particular concern for compact detectors such as SID!



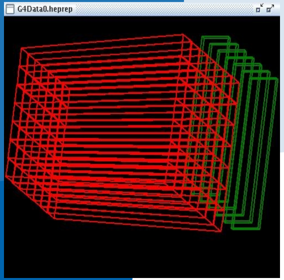
Deconvolute Dual read out from leakage

Leakage must be considered when obtaining the dual read out correction by e.g. requiring the π shower to be fully contained.
If this is not done correctly leads to overcorrection!



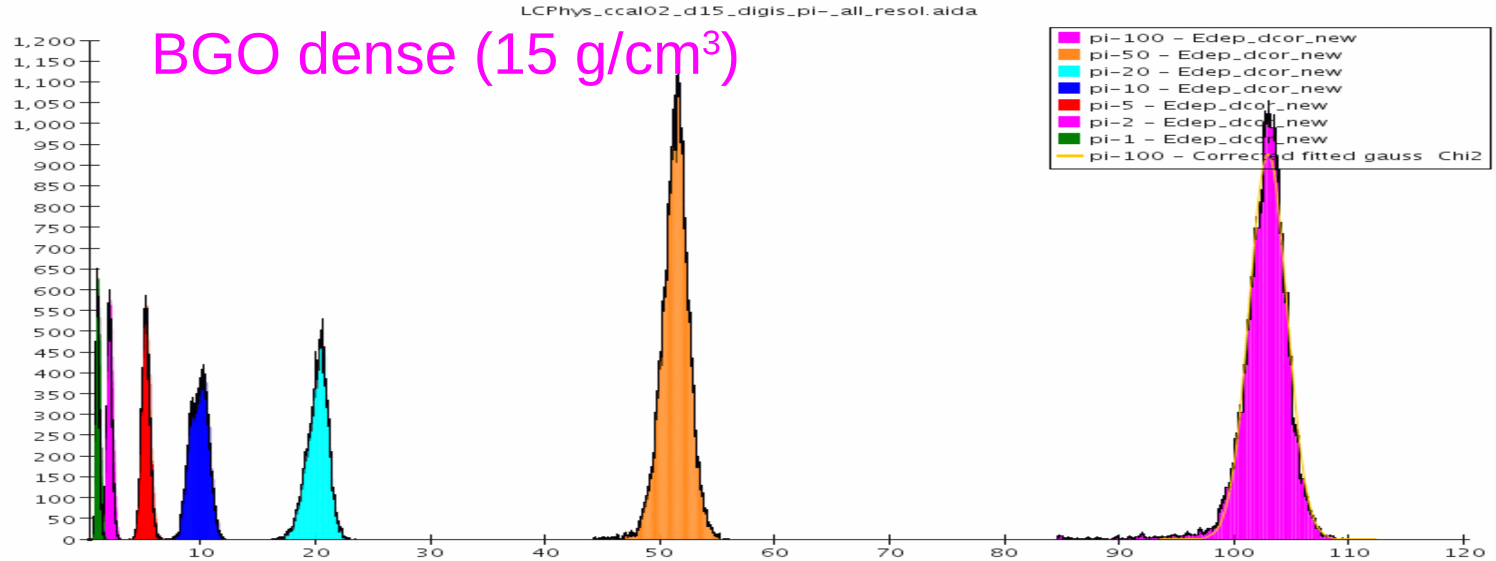
Segmentation can be used to correct for leakage:

Giovanni Pauletta and Anna Driutti have developed an Algorithmn to correct for leakage

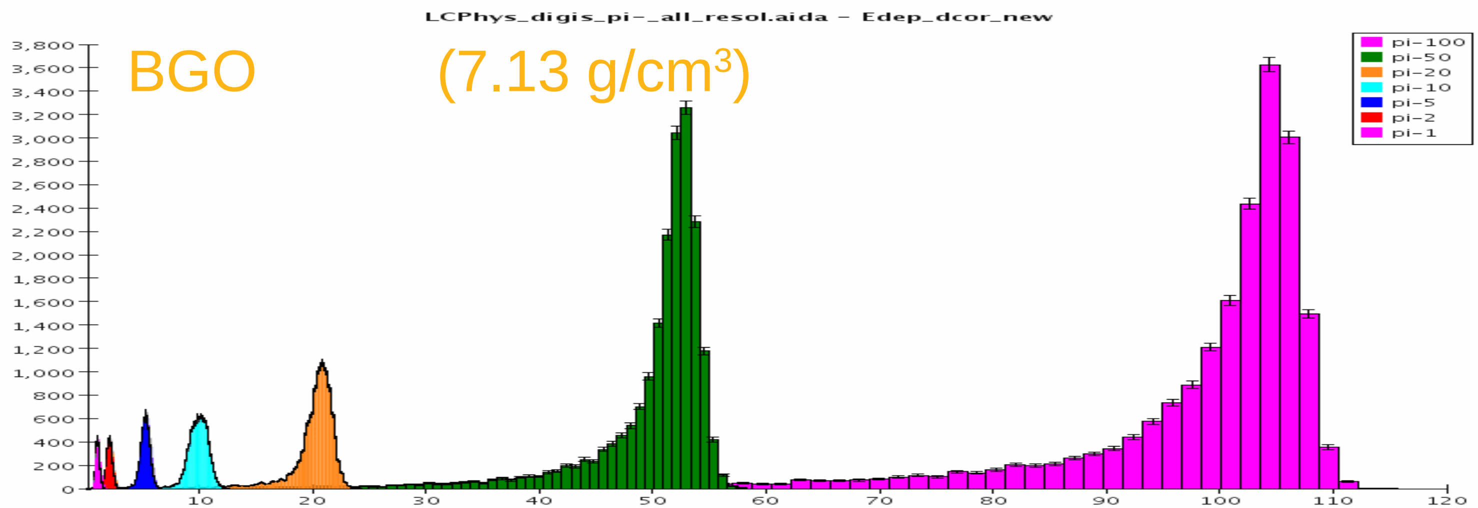


Corrected single π^- response

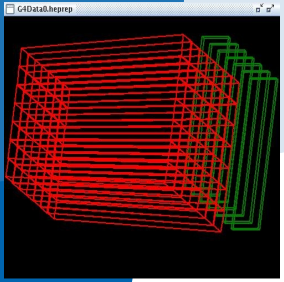
Events



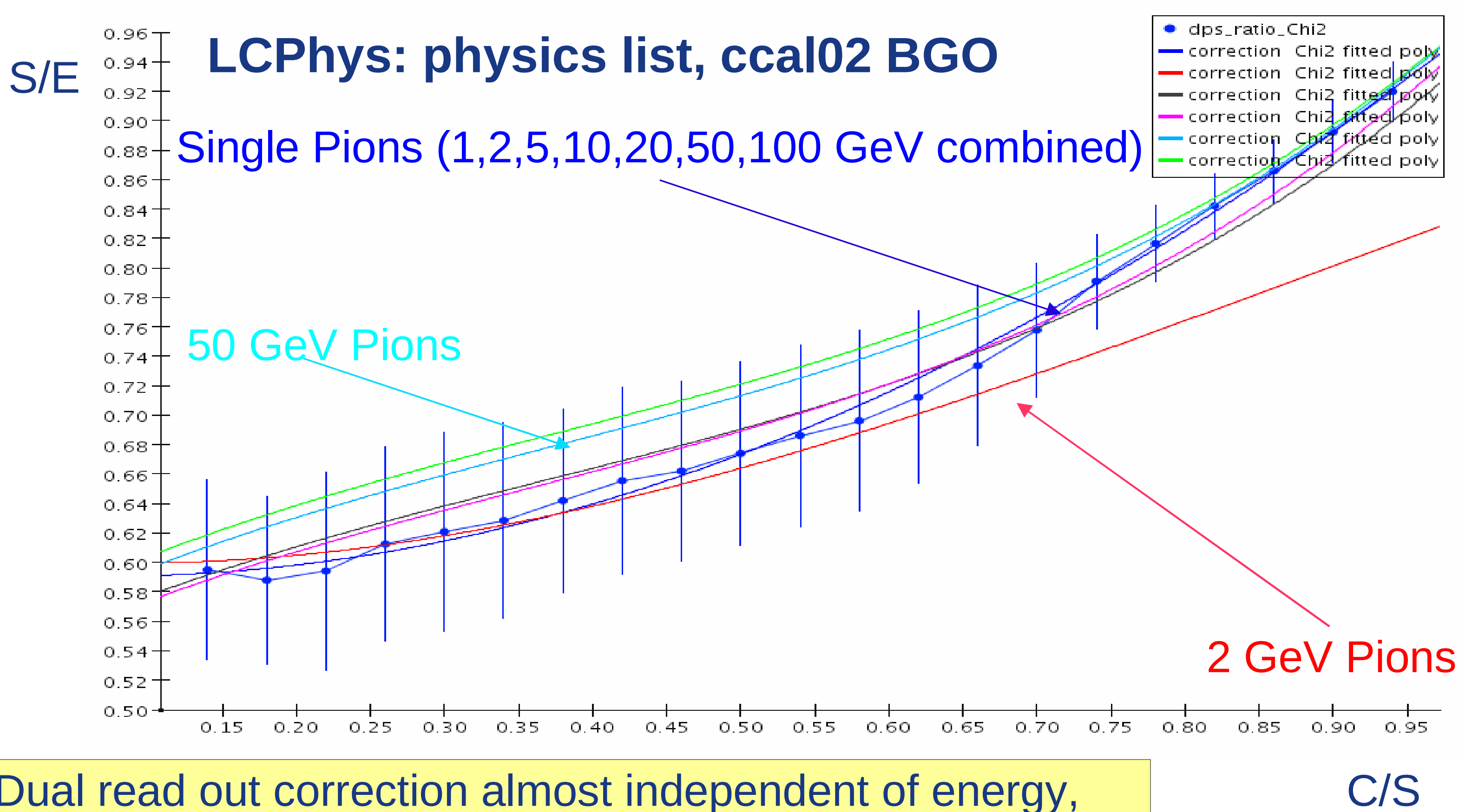
Events



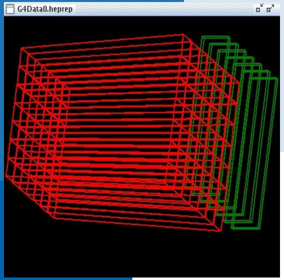
Energy in GeV after dual read out correction



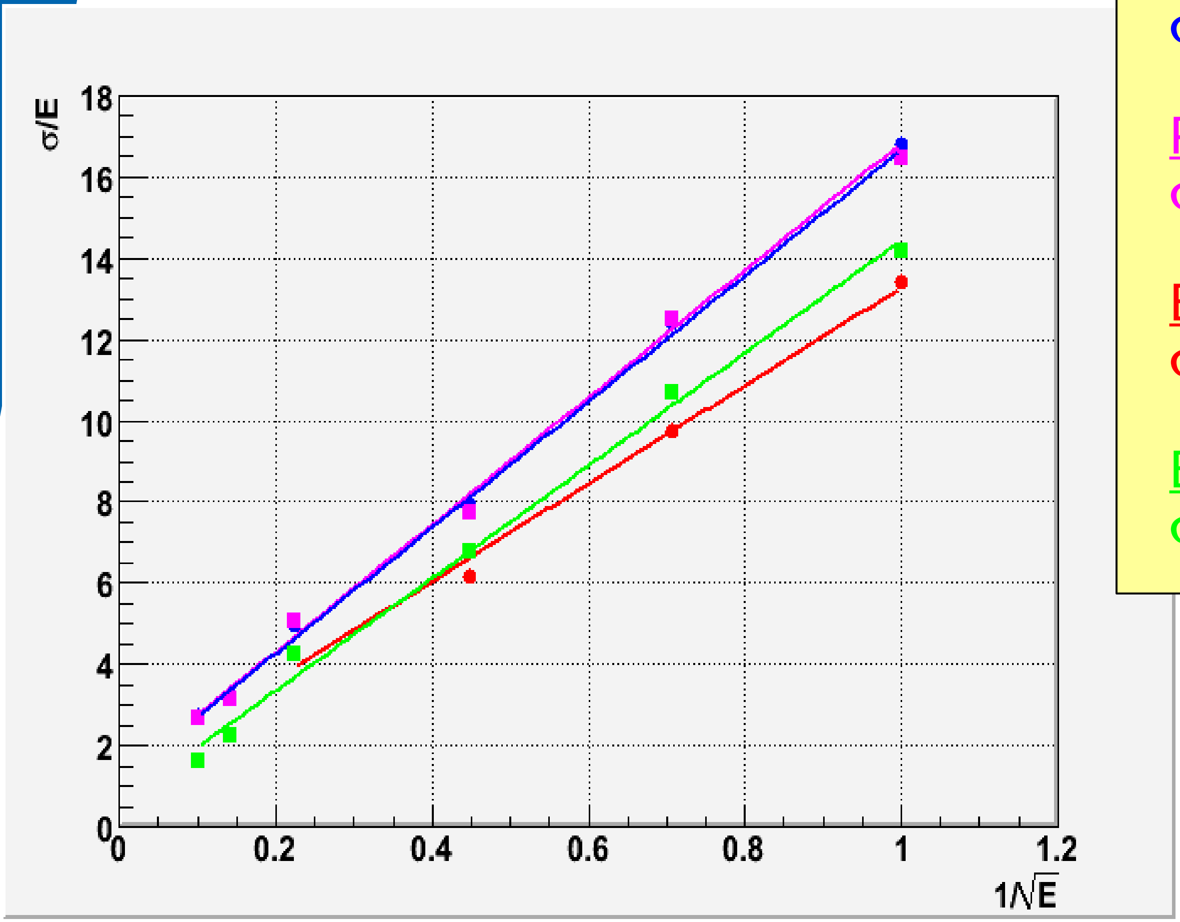
Correction function as function of energy



Note! Dual read out correction almost independent of energy, but it's worth exploring if we can improve energy resolution with energy dependent correction function



Single π⁻ resolution for different detector configurations



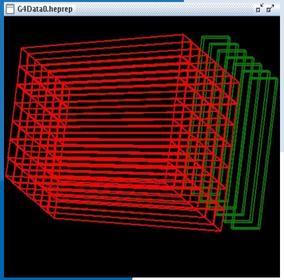
BGO,LCPhys:
σ(E)/E=1.2 + 15.6/sqrt(E) %

PbWO4, LCPhys:
σ(E)/E=1.2 + 15.5/sqrt(E) %

BGO, QGSP_BERT:
σ(E)/E=1.2 + 12.0/sqrt(E) %

BGO(dense),LCPhys:
σ(E)/E=0.6 + 13.8/sqrt(E) %

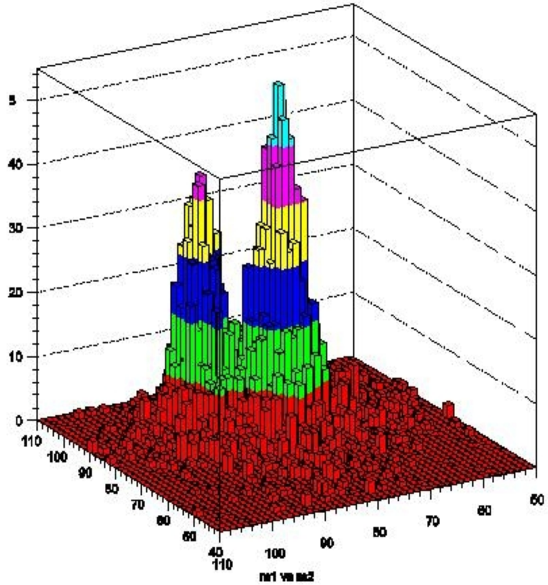
Using global dual read Out correction → can be Improved using energy Dependent correction.

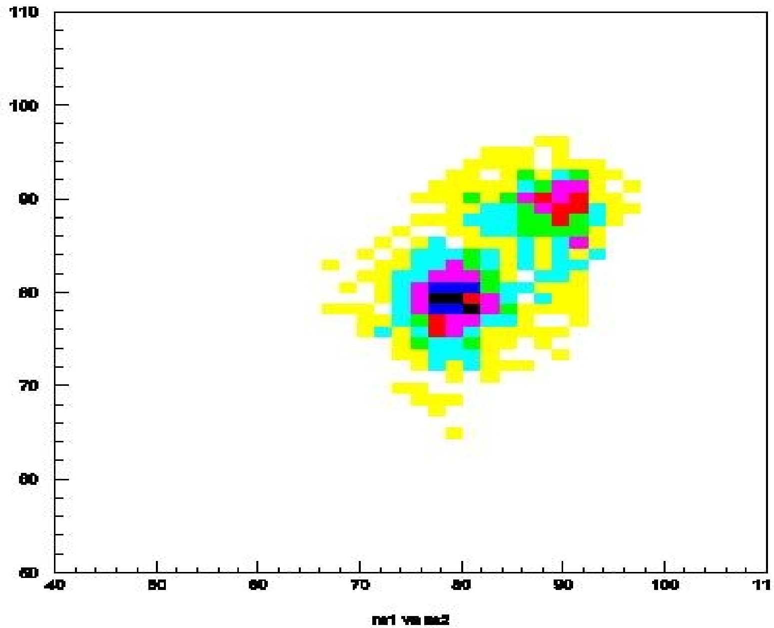


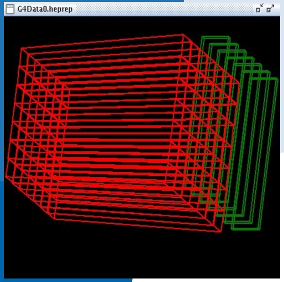
Jet reconstruction performance

WW vs. ZZ final states 5T Field using tracks to correct Displacement of charged tracks in magnetic field.

(Adam Para, Hans Wenzel,Nayeli Azucena Rodriguez Briones)



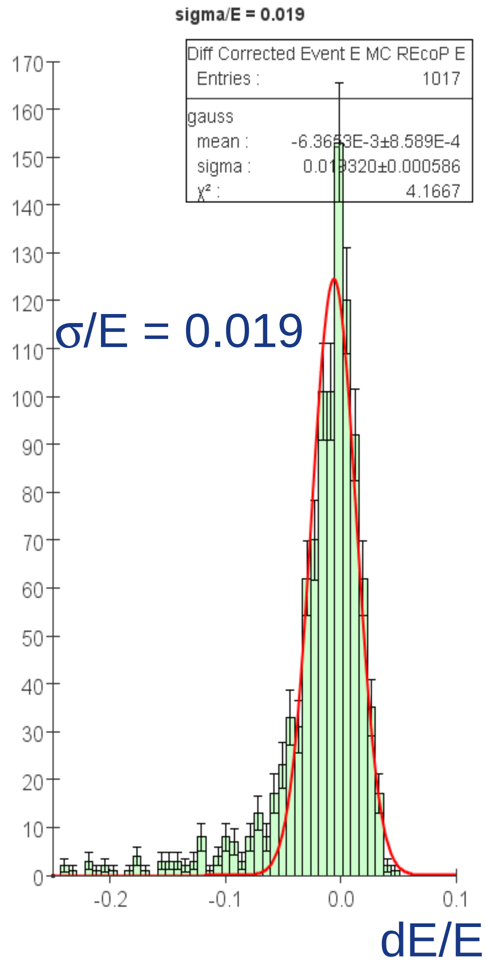


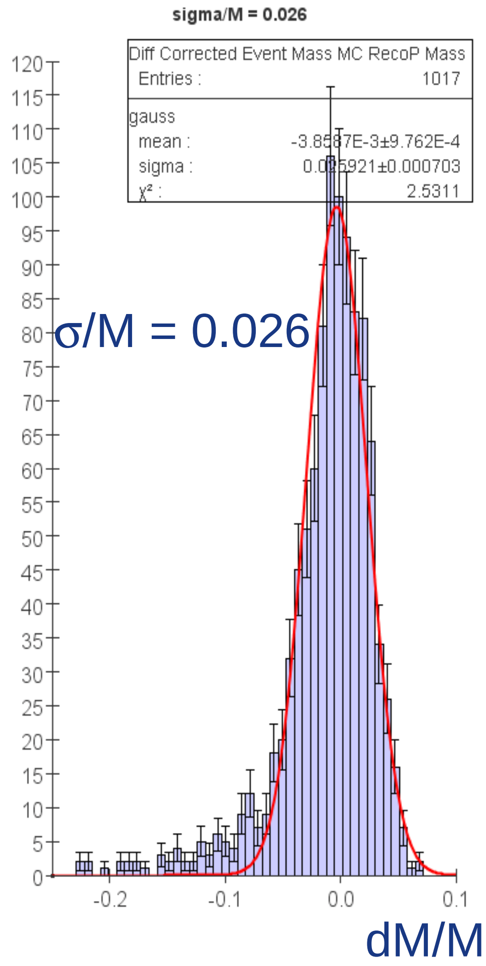


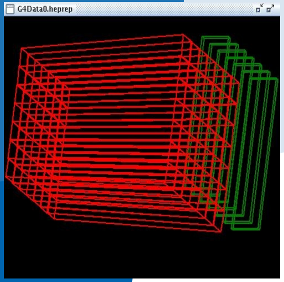
Steve Magill

Detector – CCAL002
CAL Threshold – 1/50 mip
CAL Timing cut – 100 ns

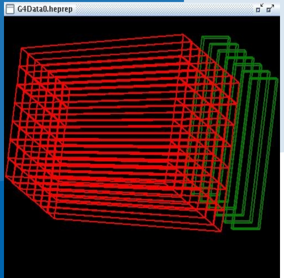
~ Z-Pole performance – C/S + PFA Mip-finder
104 GeV (Total E) Zs @ 90 degrees, Z -> qq







Can we trust the Monte Carlo?



Spectrum of Cerenkov photons

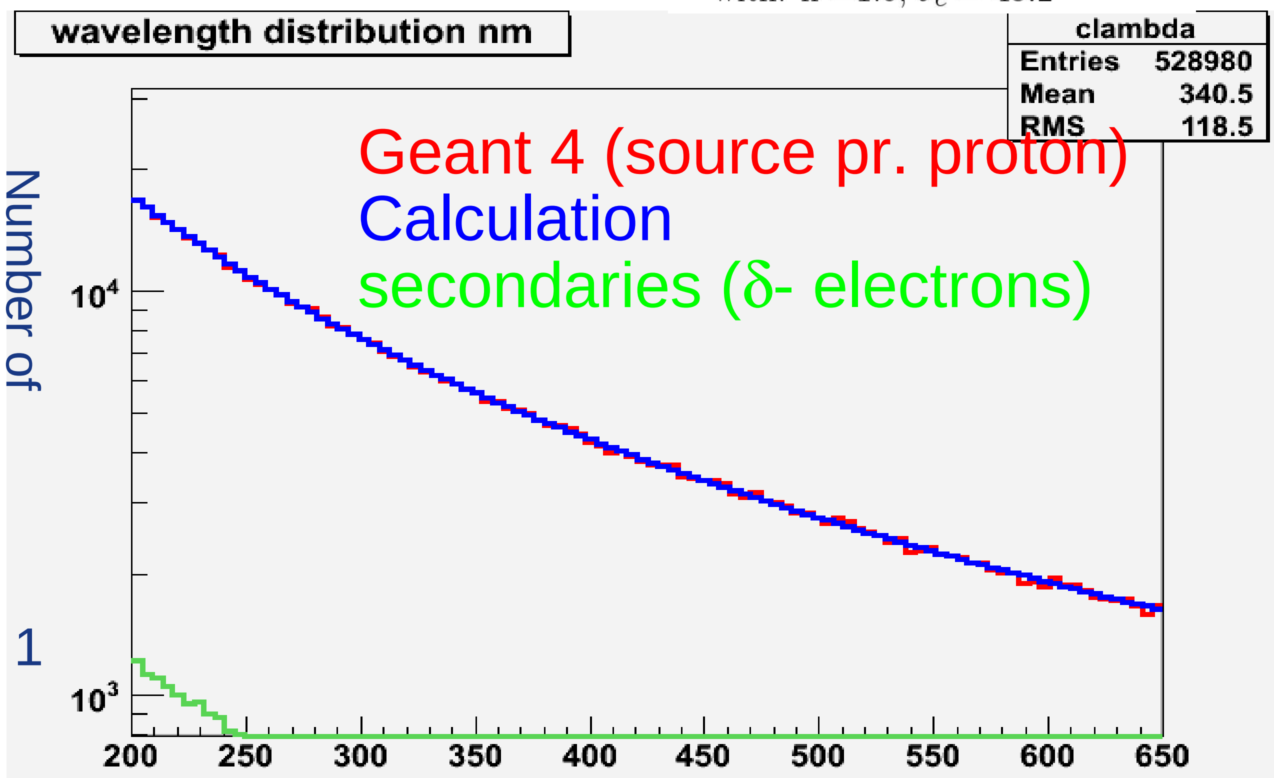
$$n_{photons} = 2\pi\alpha \sin^2\theta_c \cdot \int_{\lambda_2}^{\lambda_1} \frac{1}{\lambda^2} d\lambda$$

where

$$\cos\theta_c = \frac{1}{\beta n}$$

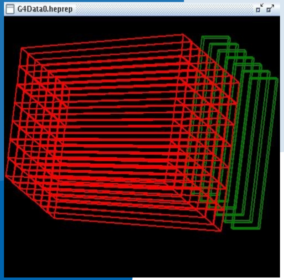
with: n =1.5, $\theta_c = 48.2^0$

Number of Photons

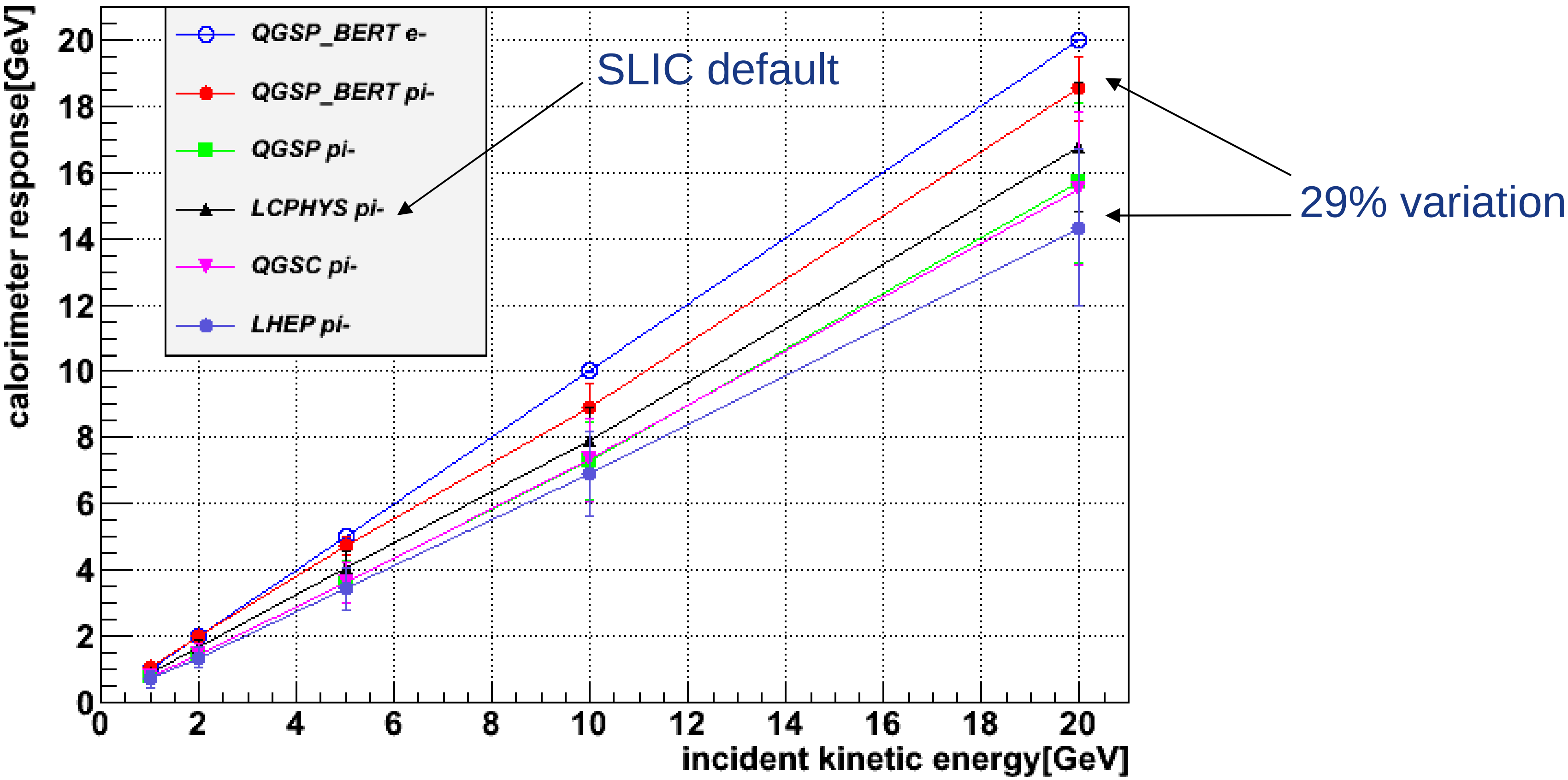


λ [nm]

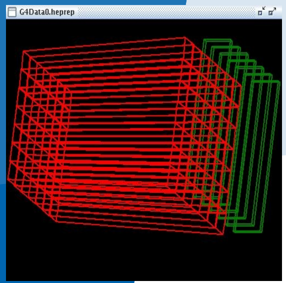
expect ~ 526 photons,
Geant 4 predicts 528+/- 1



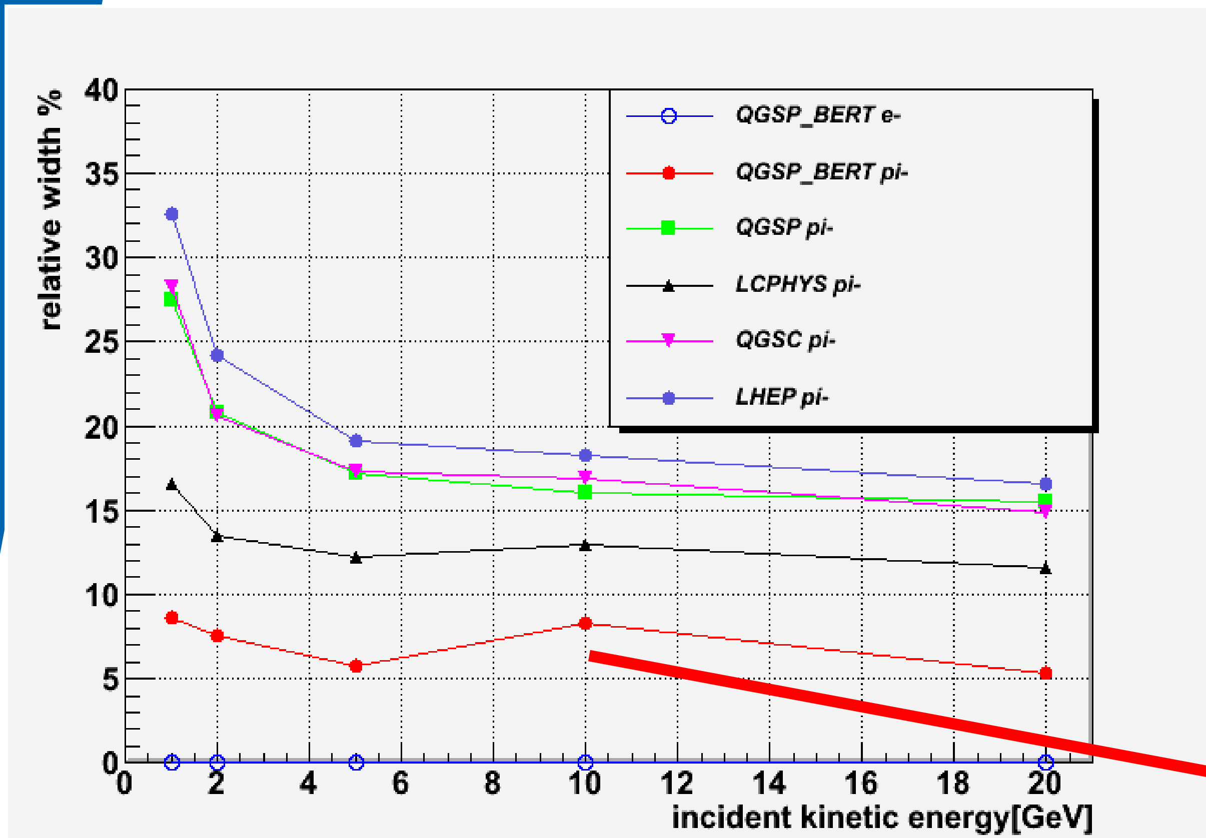
BGO Calorimeter response for different physics models

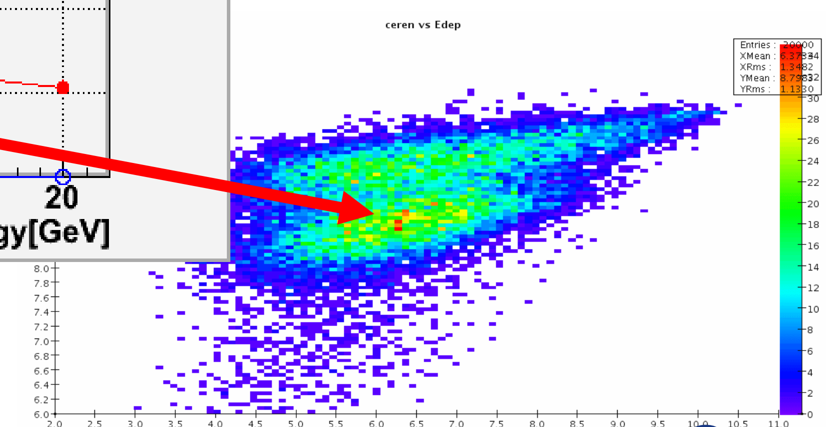


Particles produced within the calorimeter!
No threshold! → all energy deposition are added up



BGO relative width of energy response to charged pions for different physics lists

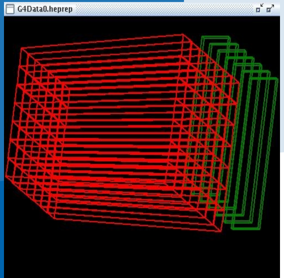




E

C

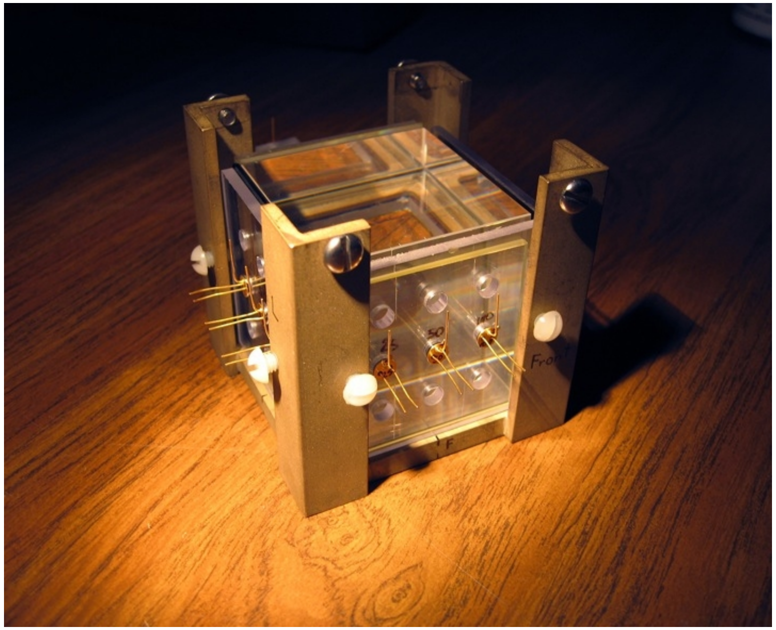
Geant 4 collaboration is aware of that!

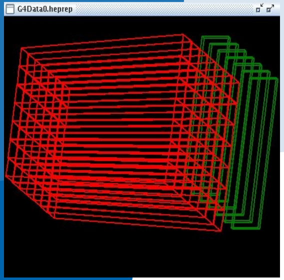


Crystals in a Test Beam

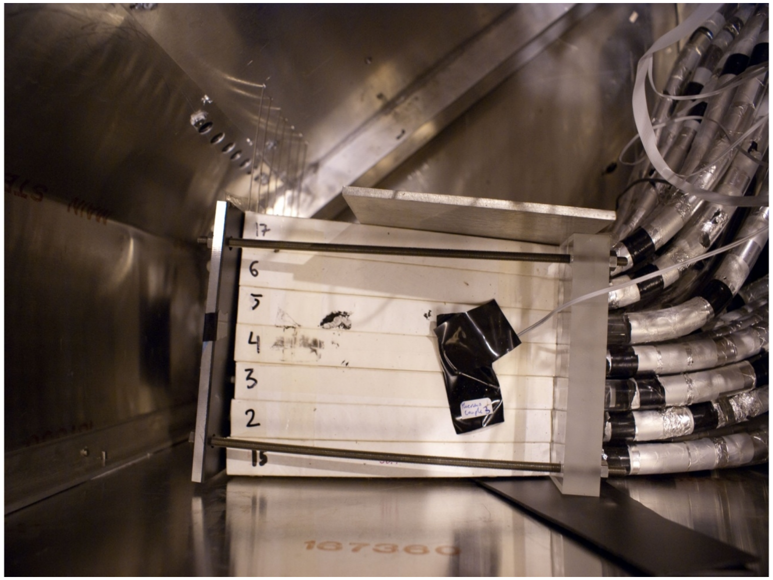
<u>Single crystal studies:</u>

- Scintillation and Cerenkov light yield
- With different filters
- With different photo detectors
- Position dependence
- Angular dependence
- Angular distribution of Cerenkov light in a shower
- Time profiles
- Compare with detailed Geant 4 simulations.

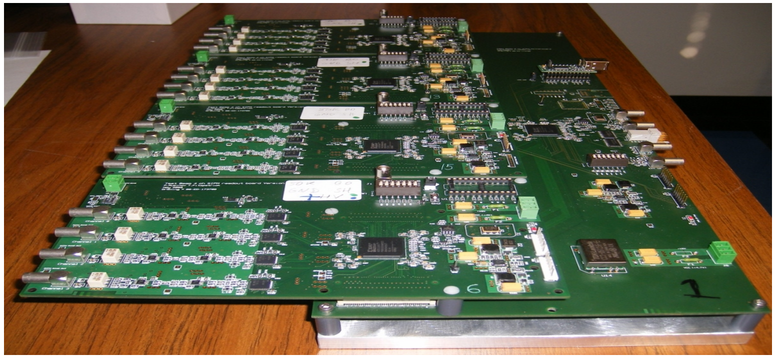


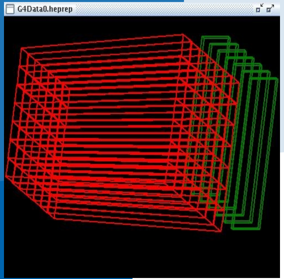


Crystals in a Test Beam



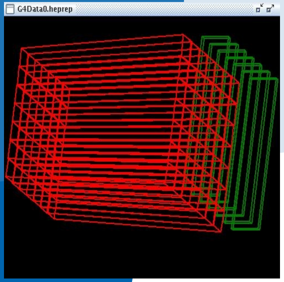
- CMS EM test module (University of Iowa)
- 49 PbWO4 crystals, photomultipliers,light guides
- Sent over from CERN
- Support structure under construction
- (Short term) plan:
  - Re-assemble the test beam module
  - Establish the performance (resolution) for electrons using the original PMT's
  - Equip crystals with IRST SiPM's, direct comparison of the resolution



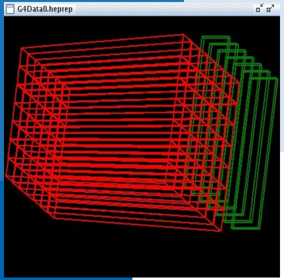


Conclusions

- A totally active dual read out calorimeter has been implemented within the SID software framework.
- Algorithms have been developed to detect and correct for leakage.
- Algorithms have been developed to correct for magnetic field affecting invariant mass reconstruction.
- PFA is being adapted to work with this calorimeter.
- Geant 4 is a a good tool to model optical processes, but will work with Geant 4 team to improve hadronic physics models.
- Need to study physics scenarios demonstrating the need for such a calorimeter.
- We are getting ready to put crystals and test beam modules into the test beam here at Fermilab.
- R&D necessary to find the right crystal (dense, affordable, UV-transparent, Scintillation and Cerenkov spectrum well separated, slow scintillation time const....)
- R&D necessary to find the right sensor (SiPMT's ?)



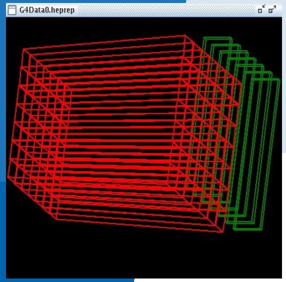
Backup slides



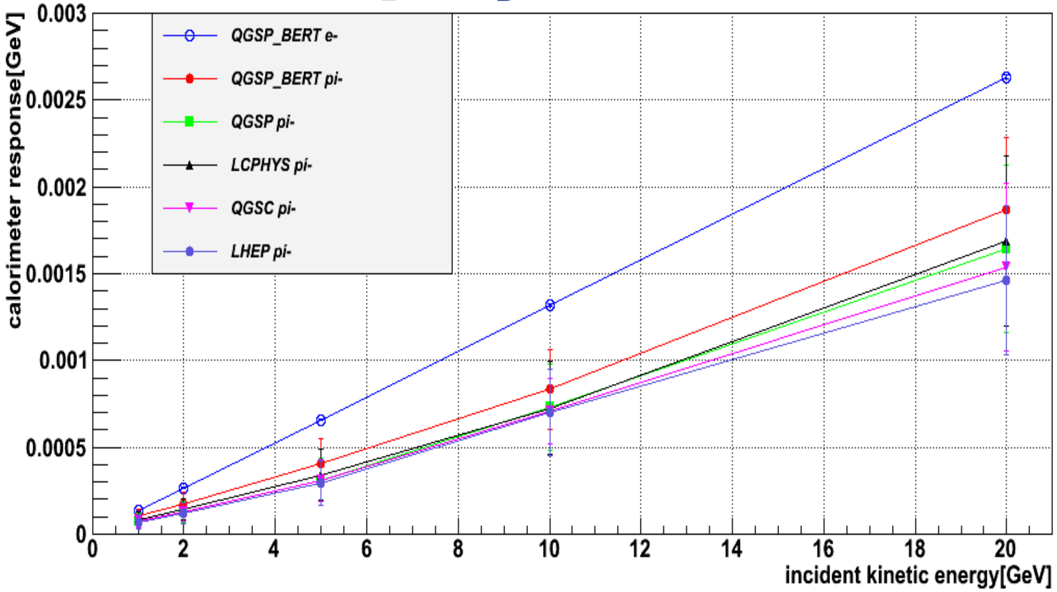
Automate analysis

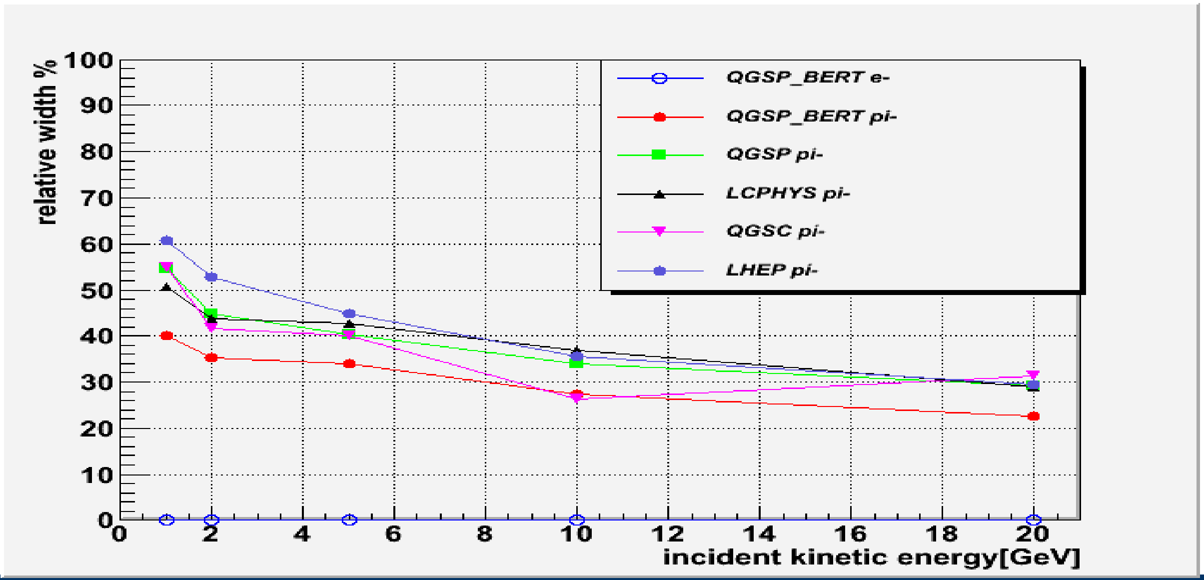
Goal: study many Detector variations, physics list etc. , obtain optimal detector configuration. Use grid to generate data sets, but also need to automate analysis like calculation of energy scale, correction functions and obtain resolution function → three lcsim modules, driven by JobControlManager, output ASCII and .aida.

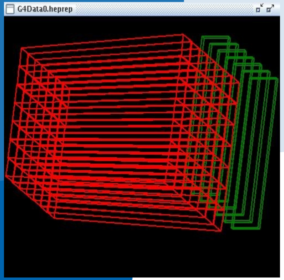
- Ecorrection: expects single electrons, obtains scale for Edep and Cerenkov response.
- DualCorrection: expects single Pions, obtains dual readout corrections combined and for various energies.
- Resolution: obtains resolution as a function of energy.



BGO Calorimeter Cerenkov response for different physics models







compact.xml/ccal02.xml

GeomConverter

Lcdd file

Edit by lcdd by hand

Lcdd file with:
- optical properties added (refraction index)
- calorimeter tag replaced with optical_calorimeter where necessary
- proper input for slic (needs optical physics enabled)

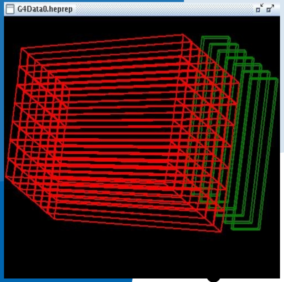
SLIC/Simulation

Analysis/Event Display

Edit by compact by hand

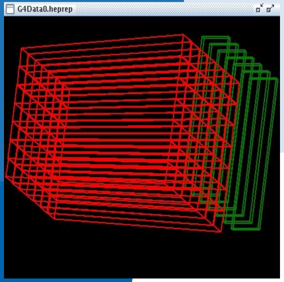
Compact with Edep_ and Ceren_ calorimeter hit collections

Hans Wenzel

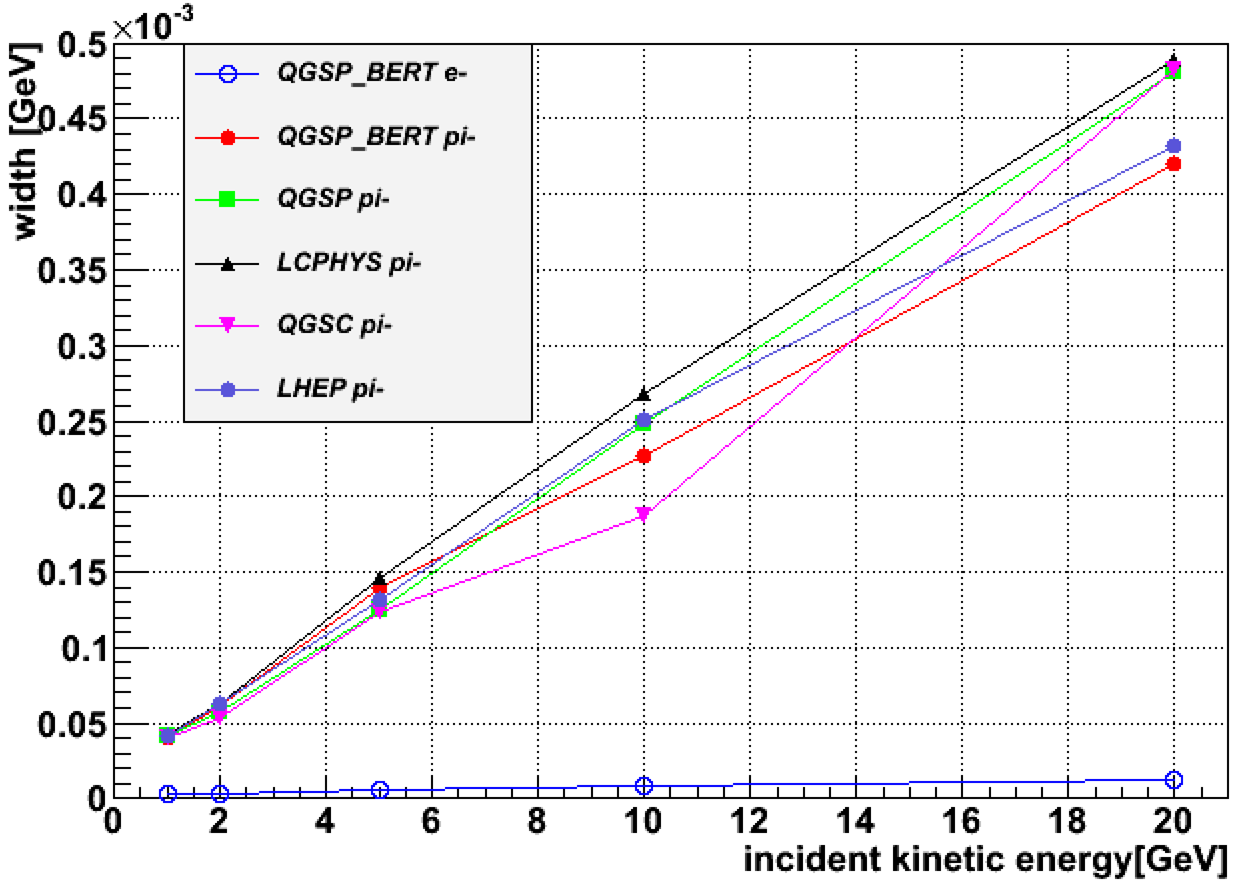


What can't be done (yet)

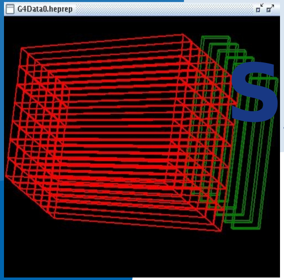
- Not the framework for detailed studies of e. g. light yield, spectral response, timing....
- Currently to do that we use GEANT 4 stand alone application. GEANT 4 has all the relevant processes: scintillation, cerenkov, wavelength shifting, dispersion, absorption, reflection ....
- Would be cool to extend SLIC to be able to do this studies:
  - Geometry description needs to be extended to describe additional optical properties e.g. the optical properties of surfaces.
  - Implementation of a photo- detector class.
  - Ability to make our own classes persistent (ROOT).
  - Large amount of optical photons → need to deal with memory issues.

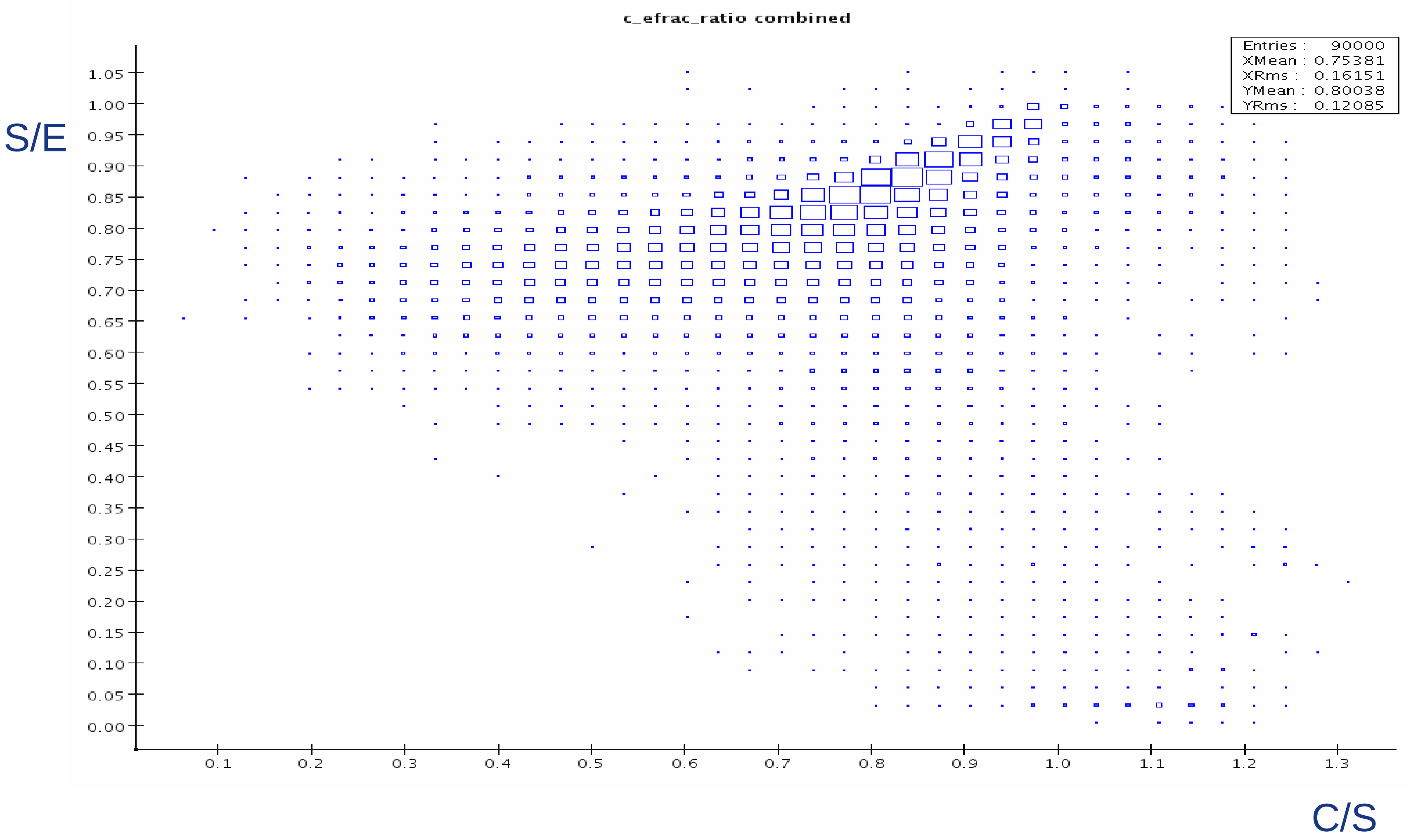


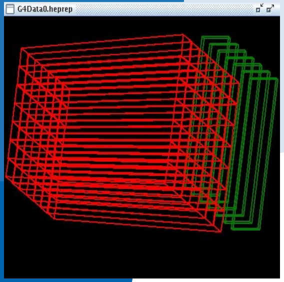
Width of cerenkov distribution



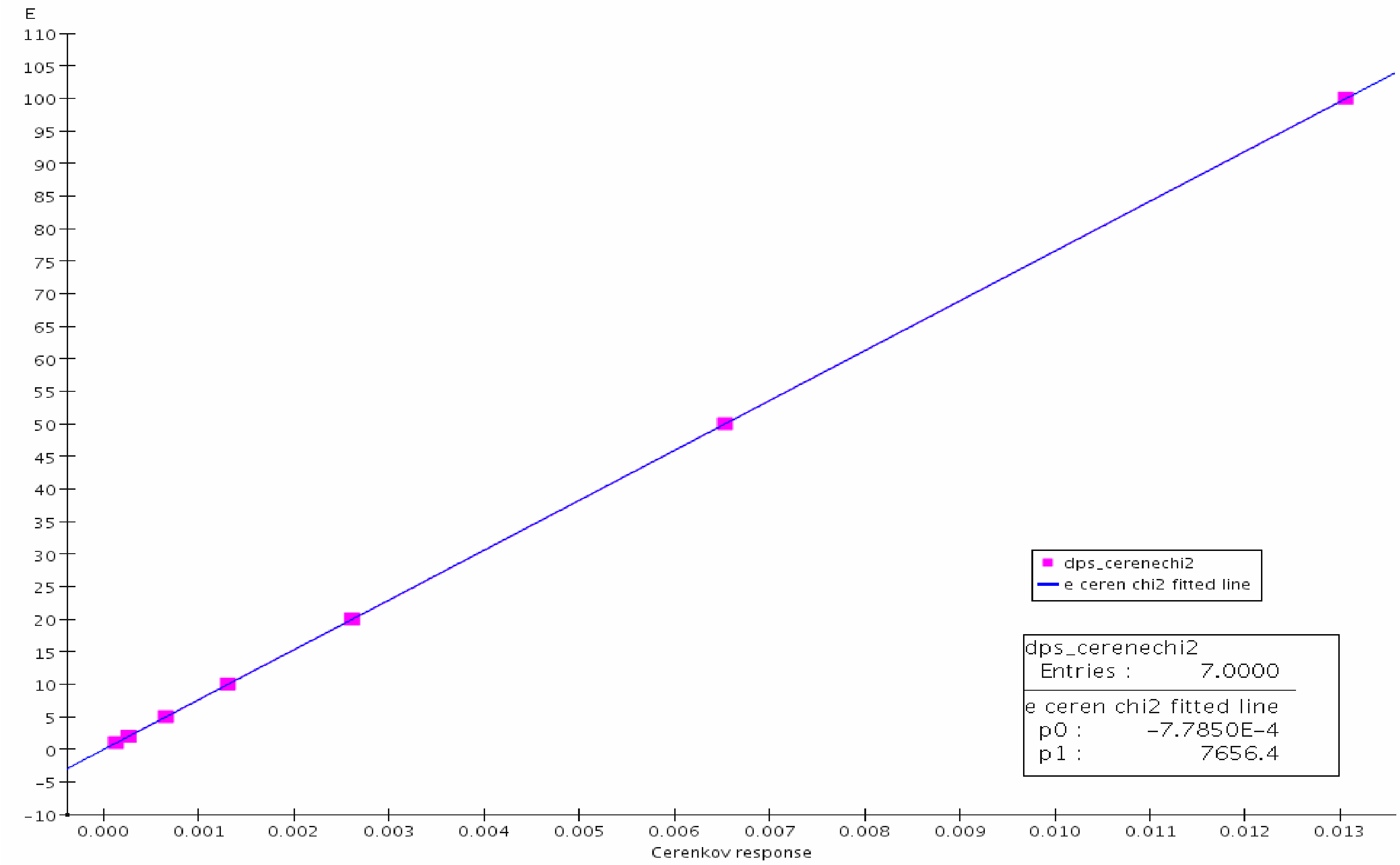
S/E vs C/S all energies combined

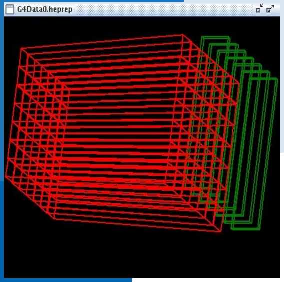




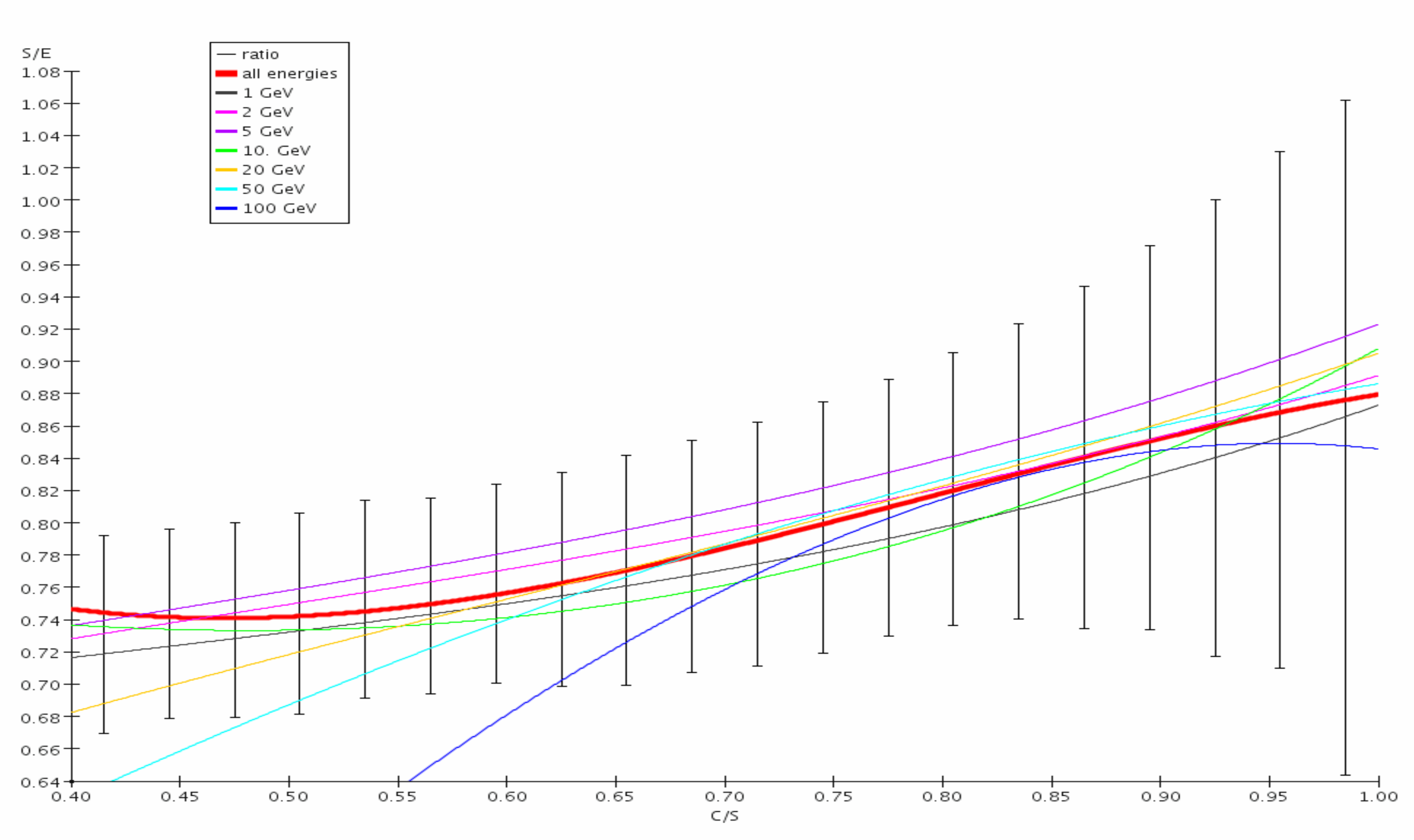


Electron Cerenkov response correction function

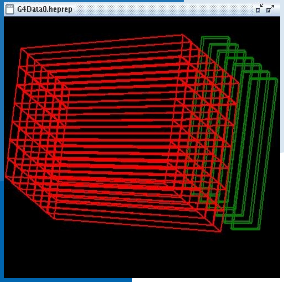




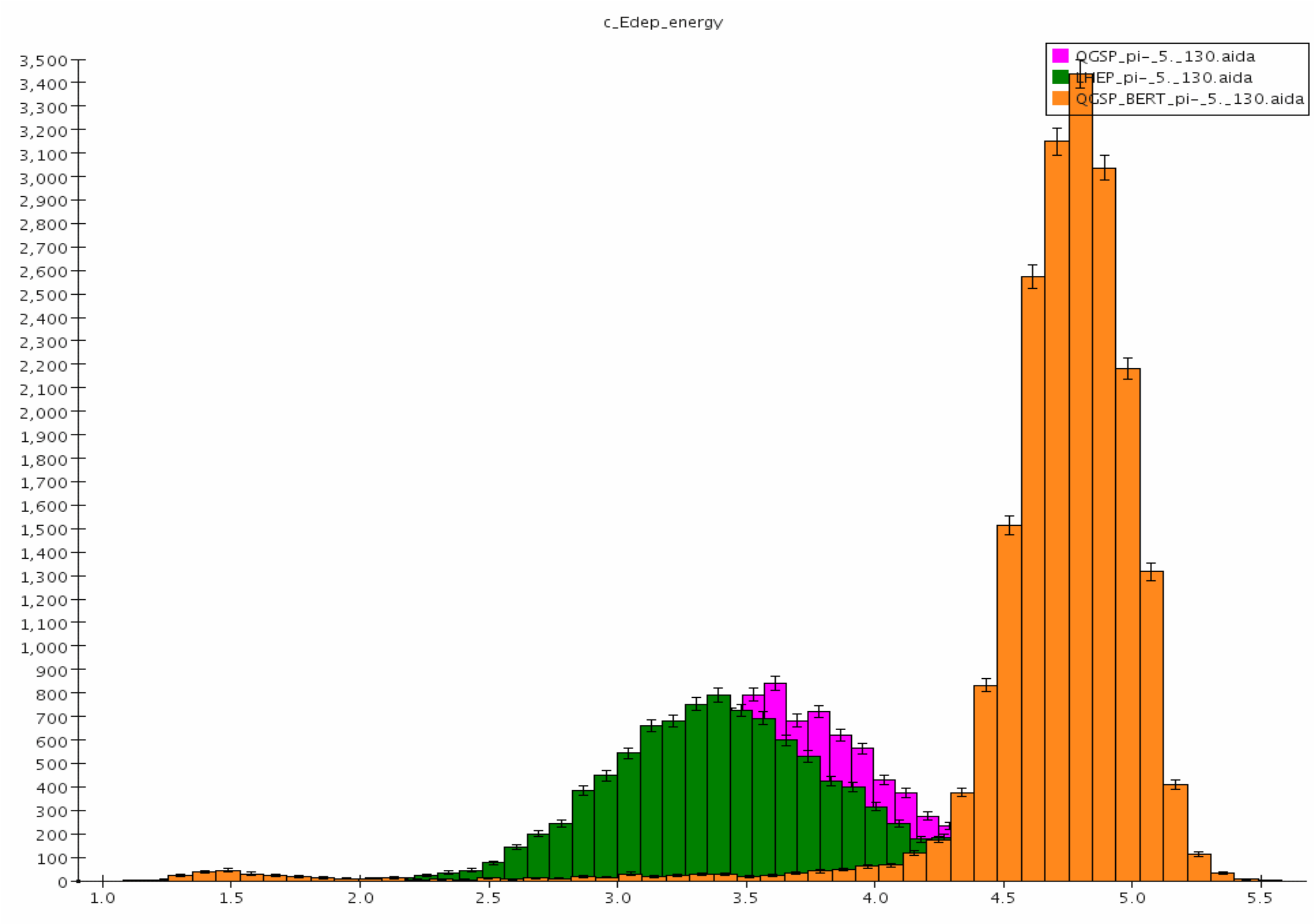
Correction function as function of energy

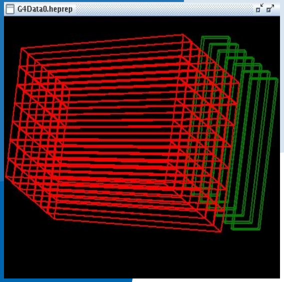


Note: For high energies (50, 100) only the low values in C/S have not been Excluded: resulting in a bad fit.
Non interacting (minimum ionizing) pions not removed

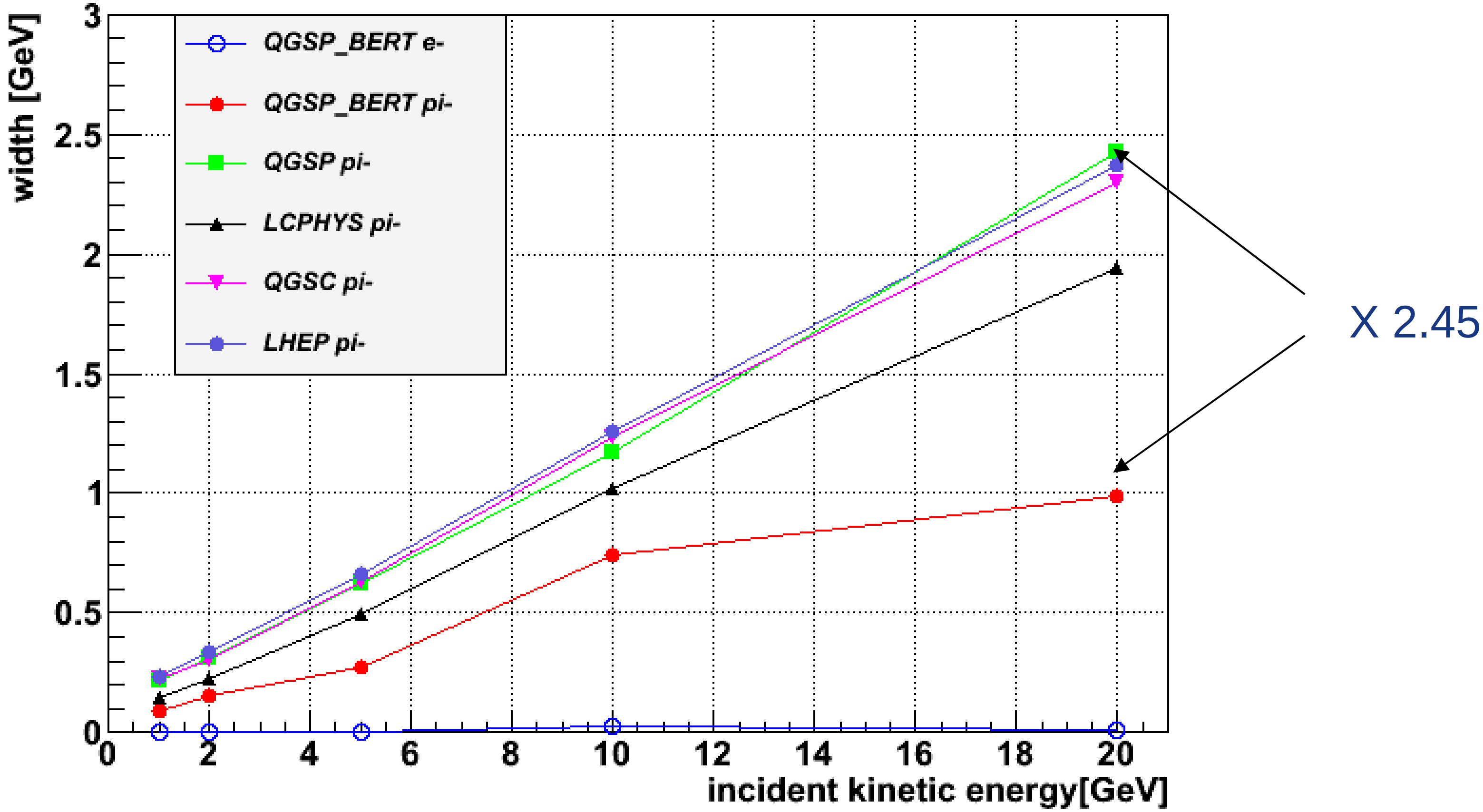


Calorimeter response for different physics models

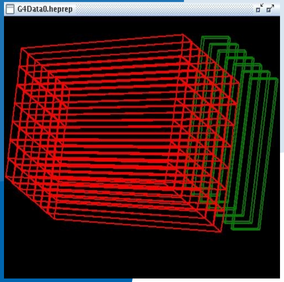


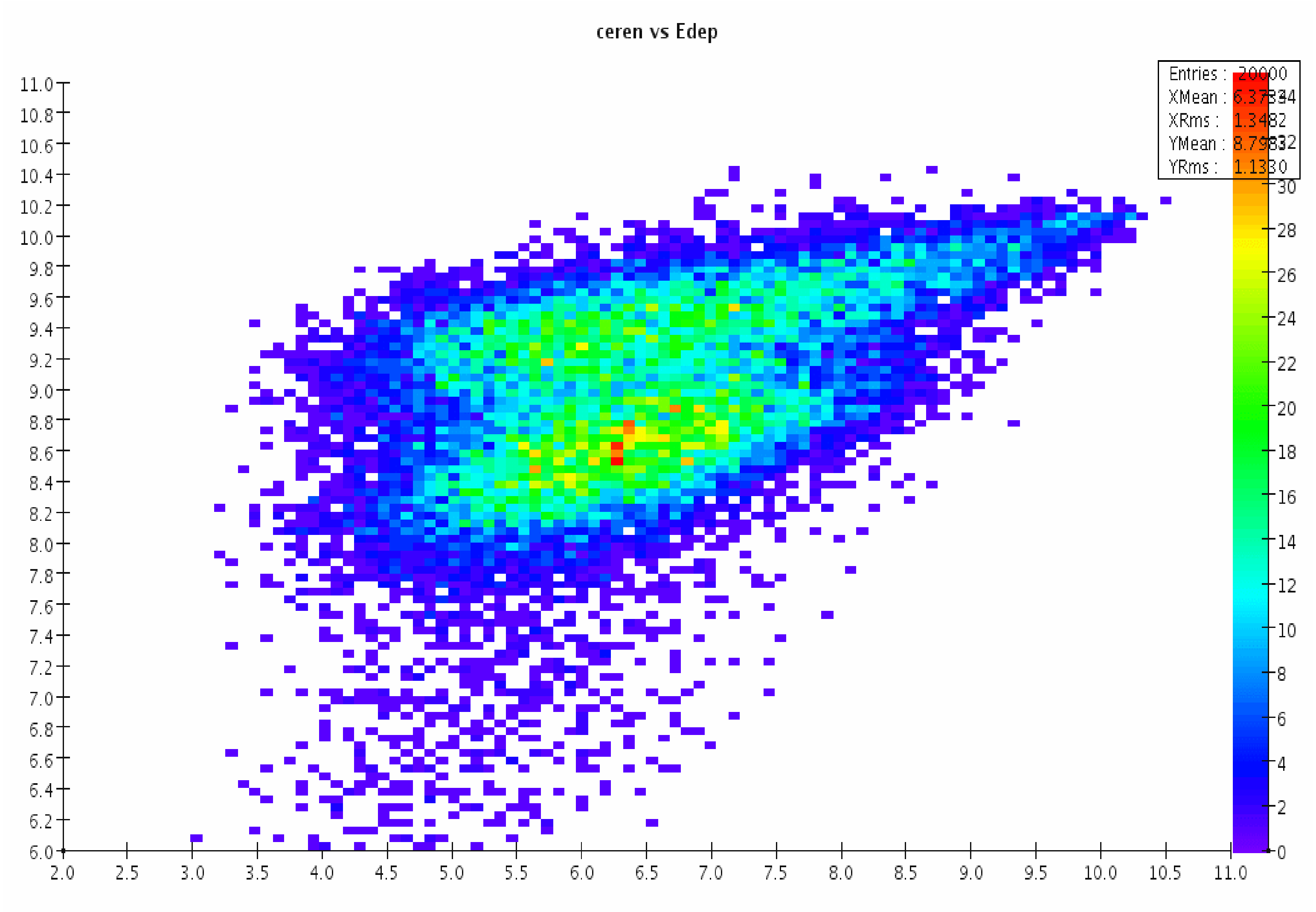


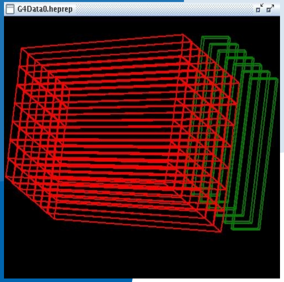
Width of calorimeter response



QGSP

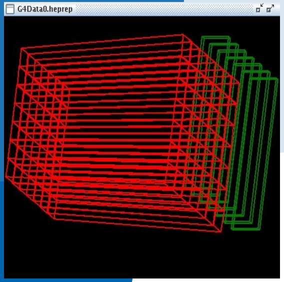

G4Data0.heprep


ceren vs Edep
Entries : 20000
XMean : 6.3734
XRms : 1.3482
YMean : 8.7932
YRms : 1.1330
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5 11.0
30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0

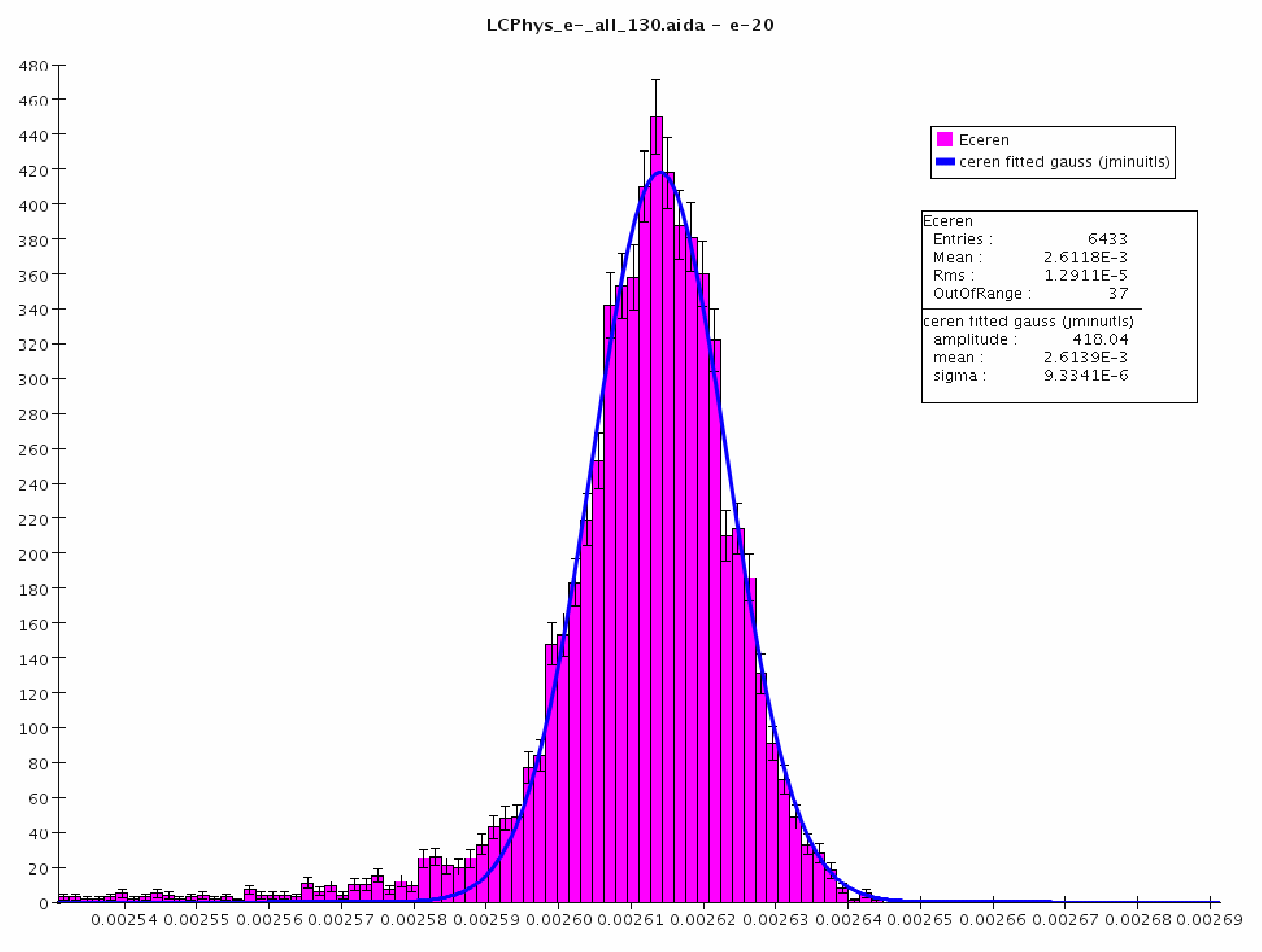


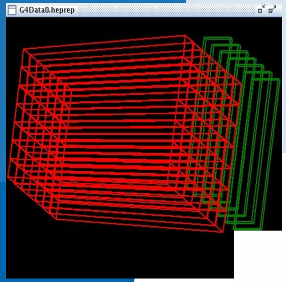
Goals

- Automate calculation of energy scale and correction functions using lcsim.org.
- Learn how to use lcsim effectively.
- Obtain correction functions/resolution curves for different
  - Physics models
  - Detector configurations (n, material....)
  - Incident angles
  - ...
- Make functions available as lcsim module.
- Study energy dependence of correction functions. Can we achieve better resolution with making energy (angular ..) dependent corrections?
- Provide material for ALCPG
- Document everything on: http://confluence.slac.stanford.edu/display/ilc/SLIC+Dual+Read+out+Tutorial

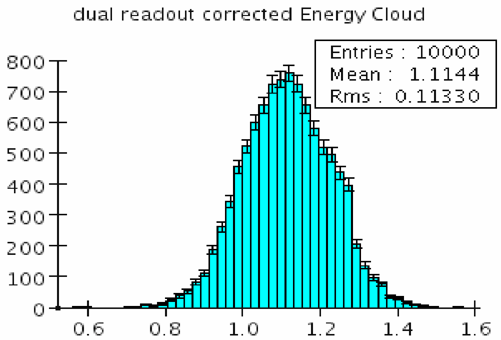


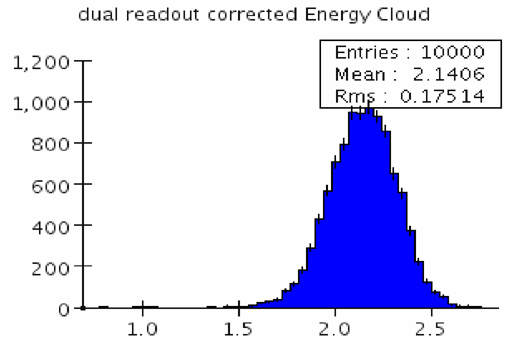
Electron Cerenkov response

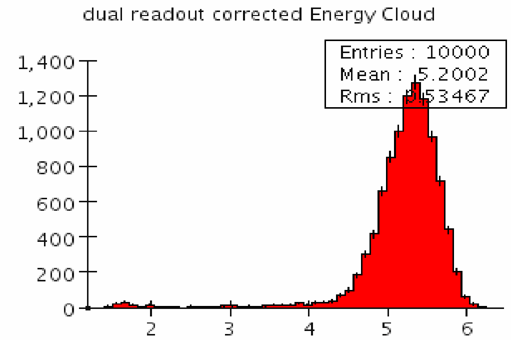


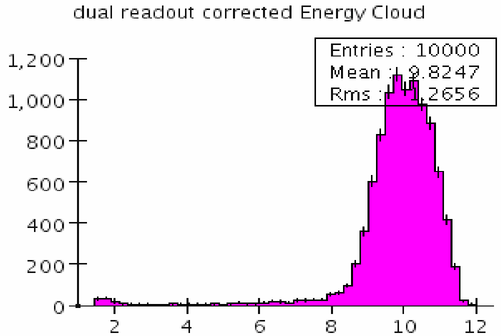


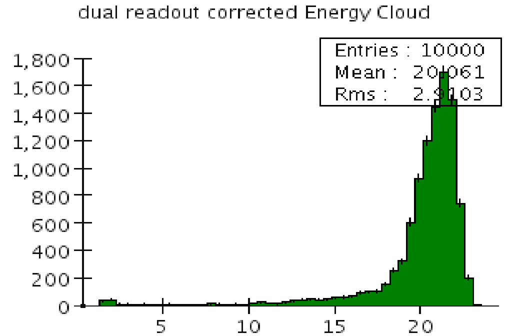
Pion response after dual corrections (all energies combined)

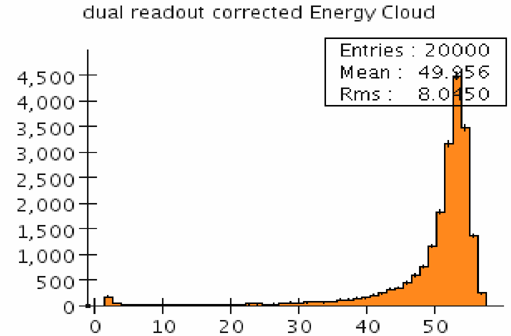


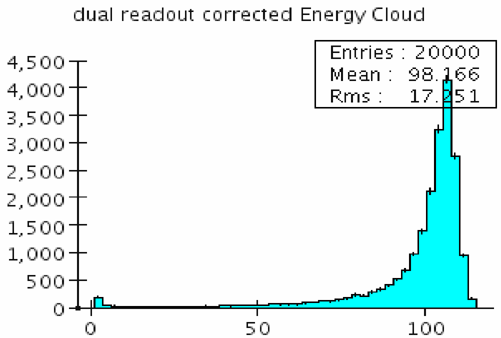


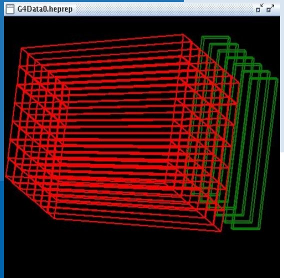




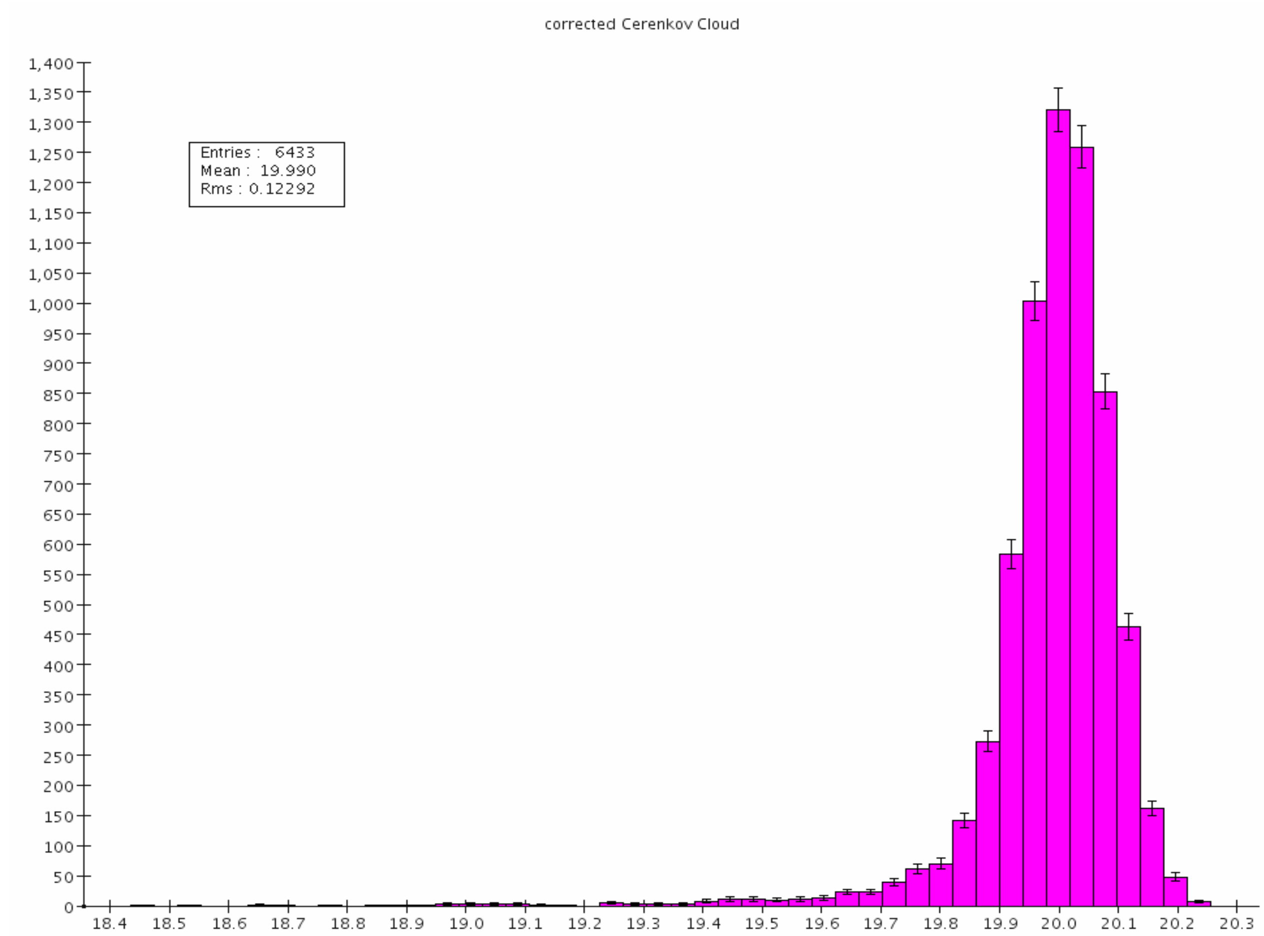


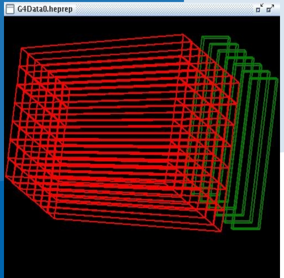






Corrected Cerenkov response





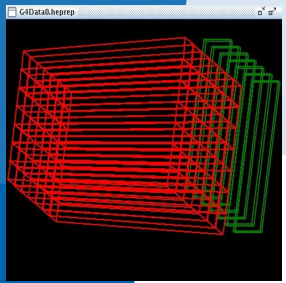
Properties of ccal02

Start with the SID02 ILC detector concept description and replace calorimeter with crystal calorimeter consisting of cylindrical layers in the central region and disks in the end caps.

				BGO		$PbWO_4$	
Name	Layers	Thickness/Layer	Segmentation	X_0	λ_I	X0	ll
		[cm]	[cm x cm]				
AL Barrel	8	3	3 x 3	21.4	1.1	27	1.3
AL Barrel	17	6	5 x 5		4.7		5.7
tal Barrel	25				5.8		7
L Endcap	8	3	3 x 3	21.4	1.1		1.3
L Endcap	17	6	5 x 5		4.7		5.7
al Endcap	25				5.8		7

Material	Density	Radiation length X0	IA length ll
	[g/cm3]	[cm]	[cm]
BGO	7.13	1.12	21.88
PbWO4	8.3	0.9	18
SCG1-C	3.36	4.25	45.6

Monte Carlo: BGO with 15.0 g/cm^3

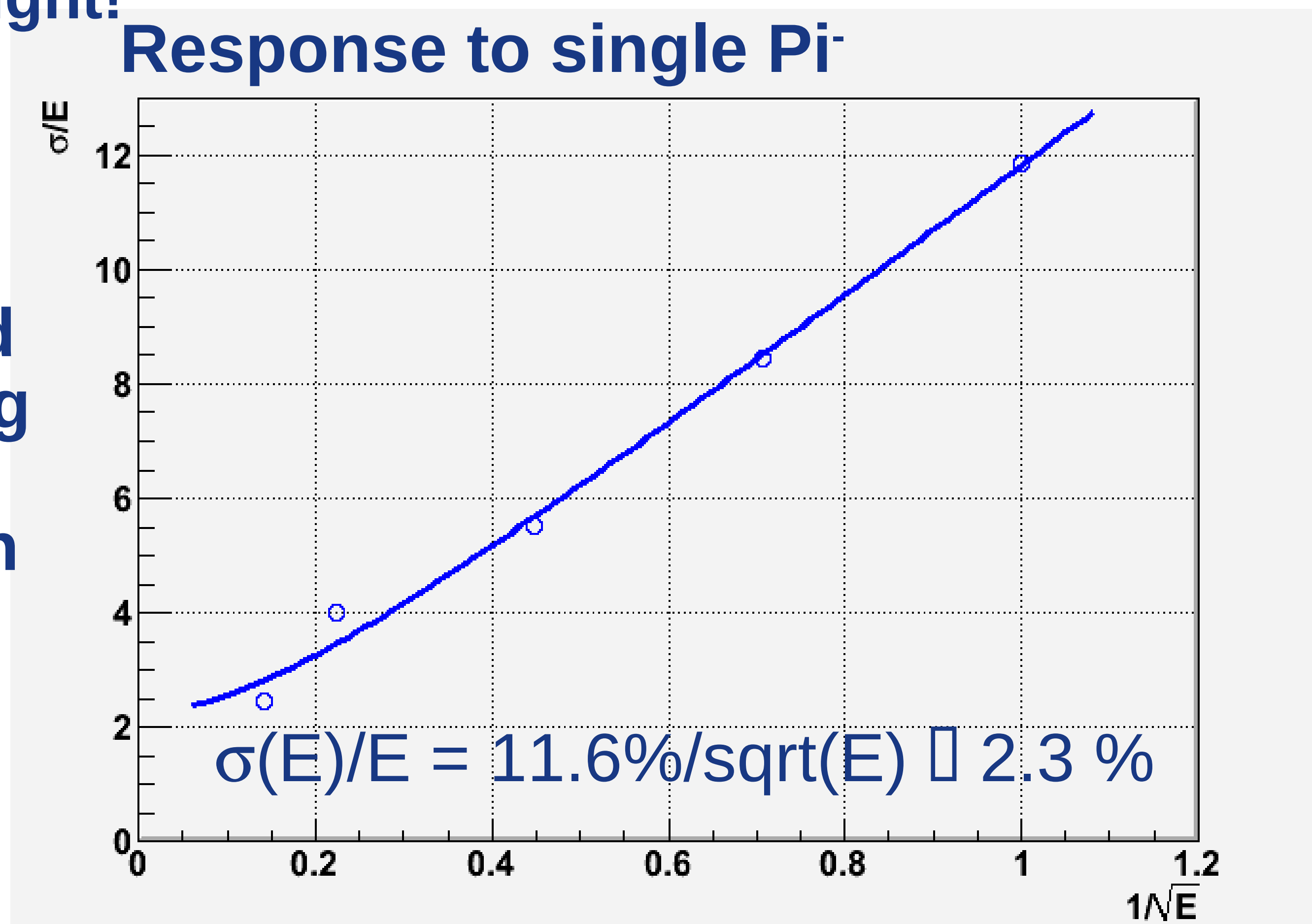


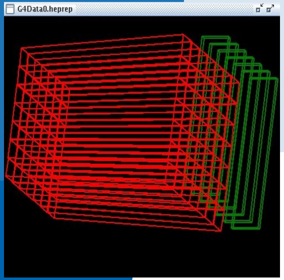
Finally: Resolution function

Did it last night!

LCPhys
ccal02 BGO
No threshold
No clustering

Cor. function (averaged)





Summary

- SLIC has been extended to allow for dual read out. Dual readout is 'completely' integrated in the SID software framework.
- Various detector versions are available (ccal02). Large data sets are available at Fermilab. http://confluence.slac.stanford.edu/display/ilc/SLIC+Dual+Read+out+Tutorial
- GEANT 4: good tool to model optical processes.
- Observe big differences when using different physics lists. Started dialog with the GEANT 4 team and will continue to work with them.